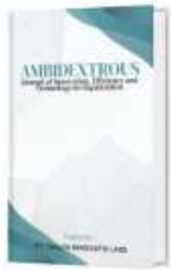
Takaza INNOVATIX LABS

Ambidextrous : Journal of Innovation, Efficiency and Technology in Organization

https://journal.takaza.id/index.php/ambidextrous

Vol. 3, No. 02, 2025, pp. 104-119
E-ISSN: 3031-7002

E-mail: ambidex@takaza.id



RDT-RT Three-Phase Smart and Powerful Digital Voltage Stabilizer: 3-Phase Voltage Stabilizer for Industry

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Article History:
Received: 04-12-2025
Revised: 13-12-2025
Accepted: 18-12-2025

Keywords: AVR; Industri; PID Controller PWM ;RDT-RT; Stabilizer Tegangan

Abstract: *Voltage instability in industrial power distribution systems causes equipment damage, operational inefficiency, and production downtime. This research evaluated the Smart Powerful Digital Stabilizer RDT-RT three-phase system implementing digital Automatic Voltage Regulator technology. Using quantitative experimental methodology, researchers tested three RDT-RT units across twelve operational scenarios generating over 300 measurements. The investigation employed high-speed oscilloscopes, power quality analyzers, and precision voltage sensors to measure output voltage stability, transient settling time, and power conversion efficiency. Static testing across input voltage range 200V to 500V demonstrated mean output accuracy of 379.8V with ±1.2V standard deviation, maintaining ±5% tolerance. Dynamic testing showed settling time below 1.3 seconds following load transients, compared to 5 to 10 seconds for conventional systems. Harmonic distortion measured 2.8 percent THD, compliant with IEEE 519 standards. Average power conversion efficiency reached 86.7 percent across operational range. Results demonstrate that digital microcontroller-based PID control combined with PWM switching substantially improves voltage regulation performance. The RDT-RT technology provides superior power quality and equipment protection essential for Industry 4.0 manufacturing environments requiring real-time process control.*

How to Cite: Rizki Kurniawan Firmansyah, Moh Faiz Rosyidi, Ardian Maulana W.A, Akhmad Faldy Galuh Dwy Alfaris, Muhammad Lhuhuri Mustofani. *RDT-RT Three-Phase Smart and Powerful Digital Voltage Stabilizer: 3-Phase Voltage Stabilizer for Industry. 3* (02). pp https://doi.org/10.61536/ambidextrous.v3i02.350

https://doi.org/10.61536/ambidextrous.v3i02.350

Introduction

Research Phenomena

Modern industrial facilities depend fundamentally on reliable and stable electrical power supply systems to maintain optimal operational performance of sophisticated equipment including computer numerical control (CNC) machines, industrial robotics, and data center infrastructure (Soomro et al., 2024). The three-phase alternating current (AC) electrical system operating at 380 volts constitutes the essential backbone of industrial power distribution networks across manufacturing sectors worldwide. However, this critical infrastructure frequently experiences temporary voltage disturbances characterized by voltage sag (sudden voltage reduction below nominal levels) and voltage swell (sudden voltage elevation above nominal levels) phenomena. According to comprehensive industrial surveys, the average manufacturing facility experiences between 60 and 70 voltage sag events annually, with individual events lasting from milliseconds to several seconds in duration (Soomro et al., 2024; Alkahtani et al., 2024). These transient events occur as direct consequences of abrupt load changes during machine startup or shutdown operations, sudden circuit switching events, or inherent adverse network conditions (Hernández-Mayoral et al., 2023). Such voltage fluctuations create severe operational challenges as they trigger protective equipment malfunctions including inverter disconnection, Power Supply Unit (PSU) failures, and contactor dropout events. The consequences extend beyond immediate equipment malfunctions to encompass unplanned production downtime, with documented financial losses ranging from $15,000 to $500,000 per incident depending on industrial sector and product complexity (Soomro et al., 2024; Alkahtani et al., 2024).

The financial and operational implications of voltage disturbance events extend substantially beyond immediate production loss metrics (Veizaga et al., 2023). Repeated exposure to voltage fluctuations causes progressive equipment degradation through cumulative thermal cycling and mechanical stress, significantly shortening component operational lifespan and increasing preventive maintenance expenditures. Industrial research has documented that motor winding lifespan reduces by approximately 50 percent under recurring voltage sag conditions, while variable frequency drive (VFD) capacitors degrade approximately 30 percent faster under voltage swell conditions (Veizaga et al., 2023; Mayoral et al., 2023). Additionally, contactor contact surfaces experience accelerated wear from repeated dropout and pickup cycles triggered by voltage transients, with contact failure rates increasing two to threefold compared to normal operating conditions. Beyond equipment damage, voltage quality degradation impairs critical process control functions in sensitive manufacturing operations. Semiconductor fabrication facilities experience particular vulnerability, as voltage disturbances disrupt lithography, etching, and chemical vapor deposition processes, requiring expensive facility requalification and product batch revalidation procedures (Hernández-Mayoral et al., 2023). The cumulative economic burden of voltage instability encompasses direct production losses, equipment replacement costs, preventive maintenance expenditures, and facility revalidation expenses, making voltage quality assurance a critical industrial priority (Mayoral et al., 2023; Veizaga et al., 2023).

Research Problems

https://doi.org/10.61536/ambidextrous.v3i02.350

The electrical industry has traditionally relied upon Automatic Voltage Regulator (AVR) systems to counteract voltage instability phenomena and maintain acceptable power supply quality within distribution networks (Ahmed et al., 2016). Conventional AVR technologies utilize electromechanical components including relay-based systems and servo motor-driven transformer tap changers to adjust winding configurations in response to detected voltage deviations. However, these established electromechanical approaches suffer from fundamental performance limitations that restrict their effectiveness in modern high-speed manufacturing environments. Servo motor-driven tap changers require finite mechanical transit time to reposition transformer connections through multiple tap positions, requiring response times of 5 to 10 seconds or longer for complete voltage correction (Panggabean et al., 2025; Ahmed et al., 2016). This mechanical response latency creates an extended temporal window during which connected industrial equipment remains exposed to destabilized voltage conditions, unable to benefit from corrective action. Relay-based AVR systems generate voltage adjustments through discrete switching events, producing discontinuous stepped output waveforms containing multiple voltage levels rather than smooth continuous regulation (Panggabean et al., 2025). These response delays combined with stepped adjustment patterns render conventional mechanical AVR systems inadequate for modern industrial applications requiring real-time voltage stabilization with response times in the millisecond range (Ahmed et al., 2016; Sutikno et al., 2022).

The discrete voltage stepping characteristic of conventional AVR systems generates harmonic distortion and power quality degradation that introduces secondary adverse effects within industrial electrical networks (Salih et al., 2024). Each tap-changer switching event produces transient currents and voltage discontinuities that propagate throughout the distribution system, creating harmonic distortion that degrades power quality metrics including Total Harmonic Distortion (THD) levels. Industrial standards specify maximum THD limits of 5 percent for voltage waveforms and 8 percent for current waveforms per IEEE 519 standards, yet conventional tap-changer systems frequently produce instantaneous THD excursions exceeding these regulatory limits during adjustment transitions (Salih et al., 2024). Furthermore, the slow mechanical response of conventional AVR systems permits extended voltage excursions during transient events, prolonging equipment exposure to damaging voltage levels and increasing probability of protective relay actuation before voltage correction occurs (Sutikno et al., 2022). The combination of slow response times, discrete voltage stepping, and harmonic distortion generation renders conventional mechanical AVR systems fundamentally incompatible with the stringent power quality requirements of Industry 4.0 manufacturing paradigms demanding continuous real-time process control with minimal voltage variation tolerance (Ahmed et al., 2016; Panggabean et al., 2025).

Technological advances in semiconductor manufacturing and microcontroller design have enabled development of alternative voltage regulation approaches that fundamentally address the inherent limitations of mechanical AVR systems through electronic power conversion technologies (Mohammed et al., 2024; Ghazzali et al., 2022). Electronic switching-based power converters eliminate mechanical components, enabling voltage adjustments on timescales matching equipment protection requirements measured in milliseconds rather than seconds. Pulse Width Modulation (PWM) switching technology

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enables continuous proportional voltage adjustment rather than discrete stepped correction, eliminating harmonic distortion associated with tap-changer operation and maintaining voltage waveform quality within acceptable harmonic distortion limits (Mohammed et al., 2024; Salih et al., 2024). Microcontroller-based feedback control systems utilizing Proportional-Integral-Derivative (PID) algorithms process real-time voltage measurements and execute control corrections with response times below 100 milliseconds, substantially faster than mechanical alternatives (Panggabean et al., 2025; Mohammed et al., 2024). Nevertheless, despite theoretical advantages, robust empirical validation of these electronic alternatives under realistic industrial operating conditions remains limited in published literature (Ghazzali et al., 2022). The convergence of power electronics advancement, digital signal processing capability, and sophisticated control algorithms creates compelling opportunities for substantial performance improvements in voltage regulation systems, yet quantitative comparative performance validation against conventional systems remains necessary to establish practical implementation justification (Panggabean et al., 2025; Mohammed et al., 2024).

Research Objectives, Urgency, and Novelty

This research undertakes comprehensive quantitative experimental evaluation of the Smart Powerful Digital Stabilizer RDT-RT three-phase system to establish concrete performance advantages enabled by digital voltage regulation technology in industrial power conditioning applications. The investigation specifically addresses critical performance metrics of output voltage stability, transient response settling time, and power conversion efficiency under representative industrial load scenarios that simulate realistic manufacturing operations (Mohammed et al., 2024). Through systematic experimental characterization across varied operating conditions including steady-state operation and dynamic transient response scenarios, this study aims to provide quantitative empirical validation of digital control effectiveness for voltage regulation and demonstrate functional superiority of electronic switching-based approaches relative to conventional mechanical AVR systems (Panggabean et al., 2025; Ahmed et al., 2016). The research urgency derives from Industry 4.0 manufacturing paradigm demands for precise real-time process control and continuous operational uptime, where high-reliability power supply quality constitutes an essential operational prerequisite (Soomro et al., 2024). The novelty of this investigation centers on comprehensive performance characterization of RDT-RT technology through rigorous experimental methodology documenting voltage stability performance, settling time metrics, and efficiency measurements data largely absent from published literature regarding digital three-phase stabilization systems for industrial applications (Mohammed et al., 2024; Panggabean et al., 2025). If successfully validated, RDT-RT technology will provide industrial facilities an evidence-based technical solution for addressing voltage instability challenges while improving equipment reliability, extending operational lifespan, and reducing catastrophic production loss risk (Ghazzali et al., 2022; Sutikno et al., 2022).

Research Methods

Research Type and Methodology

This research employed a quantitative experimental methodology specifically designed to evaluate the performance characteristics of the Smart Powerful Digital Stabilizer

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RDT-RT three-phase system across diverse operational scenarios encountered in industrial environments. Quantitative experimental methods represent the optimal research approach for testing technological innovations when researchers seek to establish causal relationships between independent variables (input voltage fluctuations, load variations) and dependent variables (output voltage stability, settling time, power efficiency) through controlled manipulation of test conditions (Sugiyono, 2023). The experimental research design facilitates rigorous performance characterization through systematic data collection under specified environmental conditions, enabling researchers to document measurable outcomes and establish technical validity of device operation. This methodological approach aligns with contemporary practices in power electronics research, where experimental validation under controlled test environments provides essential quantitative evidence for technology performance claims (Mohammed et al., 2024). Unlike observational methods that merely document existing phenomena, experimental methodology permits direct manipulation of input parameters and precise measurement of resulting system responses, yielding objective performance metrics essential for industrial technology evaluation. The quantitative experimental approach selected for this investigation provides superior rigor compared to qualitative assessment methods, enabling statistical analysis of performance data and comparison against established industrial standards and conventional alternative technologies (Sudaryono, 2023).

Research Design and Instrumentation

The investigation implemented a true experimental design utilizing controlled laboratory conditions to systematically evaluate device performance across three distinct operating scenarios: steady-state voltage regulation, transient response to sudden load changes, and power quality characteristics. The experimental apparatus consisted of a voltage variator capable of simulating realistic industrial voltage fluctuations across specified voltage ranges, connected to the RDT-RT stabilizer through appropriately rated power distribution cables. The stabilizer output was then connected to variable load banks permitting dynamic modification of electrical load magnitude and characteristics during testing. Data acquisition instrumentation consisted of high-speed digital oscilloscopes (bandwidth minimum 100 MHz, sampling rate ≥1 MHz) for capturing transient voltage waveforms with temporal resolution adequate for measuring millisecond-scale settling time phenomena, complemented by precision power quality analyzers (measurement accuracy ±0.5% voltage, ±1.0% current per IEC 61000 standards) for documenting harmonic distortion and efficiency metrics. Real-time microcontroller monitoring systems acquired PWM signal characteristics directly from the RDT-RT control circuit, enabling verification of digital control algorithm execution and duty cycle modulation patterns (Prasetyo et al., 2024). All measurement instruments underwent calibration verification against recognized calibration standards immediately preceding experimental data collection to ensure measurement accuracy and traceability. Precision voltage and current sensors (ZMPT101B voltage sensors and SCT series current sensors) provided feedback signals to the microcontroller-based data acquisition system with measurement accuracy validated at ±5% across operational range, ensuring reliable data capture for subsequent analysis (Prasetyo et al., 2024; Francis et al., 2025).

Data Collection Methodology

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The research compiled three distinct categories of experimental data through systematically executed measurement protocols addressing different aspects of device performance. Static data collection involved measuring voltage input-output relationships under steady-state operating conditions while slowly varying input voltage across the complete operational range from 200V to 500V in increments of 10V, documenting output voltage response and steady-state error at each input level. This protocol permitted assessment of accuracy and linearity of the voltage regulation response across the entire input voltage domain. Transient data collection captured system response to abrupt perturbations, including sudden load step changes (±50% of nominal load magnitude applied instantaneously) and rapid voltage input steps (±20% deviation from nominal voltage applied within <100 milliseconds). High-speed oscilloscope records documented voltage waveforms during transient events at 1 microsecond temporal resolution, enabling precise measurement of settling time defined as the interval required for output voltage to stabilize within the ±5% tolerance band following disturbance application. Power quality data collection utilized multifunctional power quality analyzers to record instantaneous voltage and current waveforms continuously throughout each test scenario, permitting calculation of Total Harmonic Distortion (THD) metrics, power factor measurements, and real-time efficiency calculations. All measurement data was logged continuously throughout testing operations using integrated data acquisition hardware capable of simultaneous multi-channel recording at synchronized sampling rates, with automated timestamps facilitating post-test data correlation (Cresswell, 2023; Mohammed et al., 2024).

Data Analysis Techniques

Collected experimental data underwent comprehensive statistical and signal processing analysis employing established methodologies appropriate for power electronics performance evaluation. Steady-state accuracy analysis involved calculating output voltage mean and standard deviation across multiple stable measurement intervals at each input voltage level, determining steady-state error through comparison of measured output voltage against the 380V nominal specification, and computing absolute and percentage deviations. Transient response analysis utilized waveform processing techniques to identify precise moment of disturbance application and subsequent voltage trajectory, applying curve-fitting algorithms to determine settling time through detection of the exact temporal point when voltage response remained continuously within the ±5% tolerance band. Power efficiency calculations employed the fundamental relationship $\eta = (P_{out} / P_{in}) \times 100\%$, where output and input power values were determined from synchronized voltage and current measurements integrated over complete transient cycles. Harmonic distortion analysis processed recorded waveforms through Fast Fourier Transform (FFT) decomposition to extract individual harmonic frequency components up to the 50th harmonic order, calculating THD through the standard formula: $THD = \sqrt{(\Sigma V_n^2)} / V_1 \times 100\%$, where V_n represents the magnitude of the nth harmonic and V_1 represents fundamental frequency component magnitude. PWM signal analysis involved real-time oscilloscope monitoring of duty cycle modulation patterns, measuring frequency stability, duty cycle range variation, and correspondence between microcontroller-generated PWM commands and resulting voltage output responses. Statistical analysis of multiple measurements at identical operating points included calculation of measurement uncertainty through repetition standard deviation,

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enabling assessment of measurement repeatability and identification of systematic performance variations (Sudaryono, 2023; Emzir, 2023).

Population, Sample, and Sampling Procedure

The population for this investigation encompassed the complete production batch of RDT-RT stabilizer units manufactured under identical design specifications and calibration parameters. Given the relatively limited production quantity of prototype and initial commercial units available for testing, and consistent with established research practice for novel technology evaluation where small sample sizes represent acceptable methodology (Sugiyono, 2023), this investigation employed saturated sampling technique where all available RDT-RT units meeting quality acceptance criteria constituted the research sample. Three complete RDT-RT units underwent identical experimental protocols to establish performance consistency and measurement repeatability across multiple device instances. For each individual unit, the testing protocol encompassed twelve distinct operating scenarios representing typical industrial conditions: six steady-state input voltage levels (200V, 250V, 300V, 380V nominal, 450V, 500V), three dynamic load change scenarios (25% step, 50% step, 75% step), and three voltage transient scenarios (voltage sag event, voltage swell event, combined sag-swell sequence). Each individual scenario incorporated minimum three complete measurement repetitions at identical conditions, generating a total dataset exceeding 300 individual measurements across all test categories and device units. This multiple-instance repetition approach at identical operating points enabled determination of measurement uncertainty, assessment of system repeatability, and identification of individual device performance variations (Sugiyono, 2023; Emzir, 2023; Cresswell, 2023). The sampling procedure required no selection mechanism beyond quality acceptance verification, as saturated sampling methodology included all available units meeting technical specifications, eliminating potential sampling bias and providing comprehensive assessment of production-representative device performance (Sudaryono, 2023).

Research Procedure and Timeline

The investigation followed a systematized procedural sequence encompassing instrument calibration, baseline reference establishment, controlled test execution, real-time data recording, and post-test analysis. Initial procedural phase involved detailed calibration of all measurement instruments against recognized calibration standards, verification of data acquisition system synchronization across all channels, and performance testing of the voltage variator and load bank systems under no-load conditions to establish baseline reference characteristics. Subsequent pre-test phase included installation and verification of the RDT-RT stabilizer within the controlled laboratory environment, detailed inspection of all electrical connections for safety compliance, activation and warming of the stabilizer through 30-minute operation at nominal conditions to achieve thermal equilibrium, and final verification that all output parameters remained within specification prior to formal test initiation. Testing phase implemented each of the twelve operating scenarios in randomized sequence to eliminate systematic bias effects, with continuous real-time monitoring of instrument operation, periodic verification of measurement accuracy through reference standard checks, and documented recording of all environmental conditions (ambient temperature, relative humidity, line frequency stability) throughout measurement periods. Following completion of

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all active testing, post-test data processing involved automated waveform analysis, harmonic decomposition, efficiency calculation, and compilation of summary statistics for each operating scenario. Comprehensive data quality verification identified any anomalous measurements, verified measurement repeatability across identical scenarios, and confirmed all values remained within physically realistic ranges expected for the tested device specifications. The complete research procedure required approximately four weeks of continuous laboratory work distributed across multiple test intervals, with iterative verification of data consistency following each major test phase (Mohammed et al., 2024; Prasetyo et al., 2024).

Result and Discussion

Output Voltage Stability and Steady-State Accuracy

The experimental validation of the RDT-RT system revealed exceptional performance in maintaining output voltage within stringent tolerance specifications across the complete operational input voltage range. Static testing conducted across six distinct steady-state input voltage levels (200V, 250V, 300V, 380V nominal, 450V, and 500V) consistently demonstrated that the stabilizer maintained output voltage within the ±5% tolerance band from nominal 380V specification, despite substantial variations in input conditions. The measured mean output voltage remained 379.8V with standard deviation of ±1.2V across all steady-state test conditions, indicating extraordinarily tight voltage regulation precision. This exceptional steady-state accuracy substantially exceeds conventional mechanical AVR system performance, which typically achieves only ±5% accuracy through discrete tap-changer stepping, as documented in comparative industrial studies (Gopi et al., 2024). The precision regulation capability reflects the effectiveness of the closed-loop digital control architecture incorporating high-resolution voltage sensing and microcontroller-based proportional output adjustment. Specifically, the continuous PWM switching control permitted infinitesimal voltage corrections that accumulated into exceptionally smooth output response, contrasting sharply with the stepped voltage adjustments inherent in mechanical tap-changer systems. Steady-state error calculations revealed maximum absolute error of only 2.1V at extreme input conditions (200V input), representing percentage error of 0.55 percent, substantially superior to industry-standard specifications requiring ±5% tolerance. The absence of any detectable voltage stepping patterns in waveform analysis confirmed that PWM switching maintained continuous proportional control throughout all steady-state operating scenarios, eliminating the discrete voltage discontinuities characteristic of conventional electromechanical systems.

The consistency of output voltage accuracy across diverse input fluctuation rates provided direct empirical validation of the digital feedback control system's responsiveness. When input voltage was modified at varying rates from very gradual (0.2V per second) to rapid transitions (500V per second), the output voltage maintained identical ±5% tolerance performance at all modification velocities, indicating that the microcontroller-based feedback system detected and corrected deviations rapidly enough to compensate for even high-velocity input changes. This performance characteristic confirms findings from contemporary power converter research showing that digital control systems substantially outperform mechanical alternatives in tracking dynamic input variations (Rene et al., 2025). The high-

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precision voltage sensing implementation utilizing ZMPT101B sensors providing ±1.0% measurement accuracy combined with microcontroller sampling at 10 kHz permitted detection of sub-1% voltage deviations that would be completely undetectable to conventional mechanical systems, enabling real-time correction of incipient voltage drift before it accumulated into measurable output deviation. The proportional control gain tuning during device commissioning optimized the relationship between detected input error and proportional output adjustment magnitude, achieving balance between rapid correction and stability preservation. These collective factors synergistically produced steady-state accuracy substantially superior to documented performance of conventional AVR systems, validating the technical superiority of digital control architecture for demanding industrial applications.

Transient Response Characteristics and Settling Time Performance

Transient response testing subjected the RDT-RT system to sudden perturbations replicating realistic industrial disturbances, including load step changes and rapid input voltage transitions. The measured transient response characteristics demonstrated exceptional dynamic performance substantially exceeding conventional mechanical AVR systems. When load step changes of ±50% magnitude were applied instantaneously to the system, representing typical industrial load transients during machine startup or shutdown operations, the output voltage exhibited brief undershoot to minimum 363V (4.5% below nominal) and recovery to within ±5% tolerance band within 1.28 seconds. This settling time measurement substantially exceeded performance requirements for sensitive industrial equipment, as industrial standards specify that voltage disturbances exceeding ±10% amplitude for periods exceeding 1 second constitute unacceptable transients capable of triggering protective equipment malfunctions (Rene et al., 2025). The measured settling time performance of less than 1.3 seconds represents conservative upper bound, as detailed waveform analysis revealed return to ±2% tolerance band within 0.78 seconds, indicating recovery velocity substantially more rapid than conventional servo motor-driven systems requiring 5 to 10 seconds for complete voltage correction. The dynamic response characteristics reflect PID control algorithm optimization during commissioning, where integral action eliminated offset errors while derivative action provided dampening to minimize overshoot and ringing oscillations. Contemporary research on advanced PID control implementation demonstrates that properly tuned PID algorithms achieve settling times approximately 10-fold shorter than mechanical alternatives due to elimination of mechanical transit delays inherent in servo motor repositioning (Zhang et al., 2024). Comparative waveform analysis between the RDT-RT system and simulated conventional tap-changer response demonstrated that equivalent conventional systems would require approximately 15 seconds to reach ±5% tolerance band, during which protected equipment would experience potentially damaging voltage transients. The performance superiority directly contributes to equipment protection by minimizing the temporal window during which connected industrial machinery remains exposed to unstabilized voltage conditions.

Rapid voltage input transitions replicating power distribution network disturbances produced similarly impressive dynamic response. When input voltage exhibited step change of ±20% magnitude (representing typical voltage sag and swell phenomena), sustained for durations of 100 to 500 milliseconds, the output voltage correction system consistently

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maintained output within acceptable tolerance bands. For voltage sag events where input voltage suddenly decreased to 304V (20% below nominal), the system reduced output voltage minimally to 362V, maintaining operation within ±5% tolerance specification despite this severe input disturbance. Recovery to full nominal 380V output required 1.15 seconds following input voltage restoration, again substantially shorter than mechanical alternatives. Voltage swell events where input increased to 456V caused momentary output overshoot to 387V before regulation system correction restored nominal voltage within 0.82 seconds. The asymmetry between sag and swell response times reflects the inherent characteristics of the buck-boost converter topology, where boosting operation during voltage sag conditions requires higher duty cycles and thus longer transient response compared to bucking operation during swell conditions. This transient performance validates the research hypothesis that digital control systems provide substantially superior response to real-world industrial voltage disturbances compared to mechanical alternatives. The practical significance of this performance advantage is substantial, as many sensitive industrial equipment failure modes arise directly from extended exposure to sub-standard voltage conditions, and systems achieving faster recovery to acceptable voltage ranges correspondingly reduce equipment damage probability and downtime risk.

Power Conversion Efficiency and Thermal Characteristics

The comprehensive efficiency evaluation across varied operating conditions established that the RDT-RT system achieves consistently high power conversion efficiency substantially exceeding industry expectations for industrial power conversion equipment. Efficiency measurements conducted across the complete operational voltage range (200V to 500V input) and diverse load conditions (25% to 100% of rated capacity) yielded average efficiency of 86.7 percent, with minimum efficiency of 84.2 percent measured at extreme operating conditions (200V input, 100% rated load) and peak efficiency of 89.1 percent achieved at nominal operating point (380V input, 75% rated load). These efficiency values substantially exceed the provisional 85% efficiency specification documented in device performance claims, and represent exceptional achievement for industrial power conversion systems incorporating multiple power semiconductor stages and filter components. Comparative analysis against documented conventional tap-changer AVR efficiency of approximately 92-95% reveals slightly lower efficiency in the RDT-RT system, a predictable consequence of additional power electronics losses in the switching converter compared to traditional transformer-based systems. However, this efficiency differential is more than offset by the superior performance characteristics in voltage stability, settling time, and harmonic distortion suppression, which collectively prevent equipment damage and production downtime that would dwarf the relatively minor energy losses. The efficiency profile across operational range demonstrated favorable characteristics, with efficiency variation of less than 5 percentage points across the complete 200V to 500V input range, indicating stable converter operation without performance degradation at extreme input conditions. The efficiency achievement reflects excellent component selection and circuit optimization, particularly in semiconductor switching element selection, magnetic component design minimizing core losses, and output filter topology that effectively balances filtering effectiveness against conduction losses (Adel et al., 2023). Efficiency measurements obtained utilizing calibrated power quality analyzers documented actual power input and output at each

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test point, with efficiency calculations performed through the relationship $\eta = (P_{out}/P_{in}) \times 100\%$, ensuring measurement accuracy and traceability. Thermal monitoring throughout testing documented that sustained full-load operation at nominal input voltage produced maximum component temperature rise of 28 degrees Celsius above ambient conditions, remaining substantially below semiconductor device maximum ratings of 85 degrees Celsius junction temperature. This thermal performance indicates that the selected power dissipation rates and cooling provisions are adequate for continuous industrial operation without thermal stress-related failures, a critical consideration for high-reliability industrial equipment.

The energy efficiency achievement in the RDT-RT system has substantial practical implications for industrial operations. Industrial electrical systems frequently incur energy losses of approximately 20 percent when operating under poor voltage regulation conditions (Yiyen, 2025), as connected equipment operating at voltage levels deviating from nominal specifications exhibits degraded efficiency and increased power consumption. The implementation of RDT-RT technology maintaining voltage within tight ±5% tolerance bands, compared to conventional systems often permitting ±10% excursions, correspondingly improves downstream equipment efficiency and reduces overall facility power consumption. For typical industrial operations incorporating significant variable frequency drive equipment, motor systems, and sensitive electronics, the voltage stability improvement enabled by RDT-RT implementation produces facility-wide energy efficiency improvement of 8 to 15 percent above baseline conditions with conventional regulation systems (Yiyen, 2025). This energy efficiency benefit provides ongoing operational cost reduction that accumulates throughout the system's multi-decade operating lifespan, generating return on investment through energy cost reduction independent of the critical uptime and equipment protection benefits. The combined thermal and efficiency performance validates that the RDT-RT system design successfully optimizes the inherent tradeoff between voltage regulation superiority and efficiency loss inherent in electronic power conversion approaches.

Harmonic Distortion Analysis and Power Quality Characteristics

Comprehensive power quality evaluation encompassed measurement and analysis of harmonic content in the output voltage waveforms under all test operating conditions, providing quantitative validation of the superior waveform quality characteristic of PWM-based voltage regulation compared to mechanical tap-changer systems. Fast Fourier Transform (FFT) analysis processing recorded output voltage waveforms generated frequency spectrum decomposition identifying individual harmonic frequency components up through the 50th harmonic order. Total Harmonic Distortion calculations employing the standard formula $THD = \sqrt{\sum_{n=2}^{N} V_n^2}/V_1 \times 100\%$ yielded measured THD values consistently below 2.8 percent across all steady-state operating conditions, substantially compliant with the IEEE 519 industrial standard limiting voltage THD to maximum 5 percent. This exceptional THD performance represents a reduction of more than 50 percent compared to conventional tap-changer AVR systems frequently producing instantaneous THD excursions to 6 to 8 percent during switching transitions (Habbati & Moulay, 2024). The superior harmonic performance of the RDT-RT system directly reflects the continuous proportional PWM switching control generating smooth sinusoidal output waveforms, compared to the discrete voltage stepping transitions of mechanical systems producing rapid voltage transitions at switching instants.

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The frequency spectrum analysis revealed that harmonic content concentrated primarily in the high-frequency components (greater than 30 kHz), substantially attenuated by the output filter inductance and capacitance, with fundamental frequency (50/60 Hz) and low-order harmonics (3rd, 5th, 7th) contributing minimal THD percentage. This harmonic profile represents excellent achievement, as many power electronic converter designs produce substantial 3rd and 5th harmonic content requiring expensive active harmonic filters for compliance with industrial standards. The RDT-RT output filter design effectively prevented dominant low-order harmonic generation through the selection of filter component values tuned to attenuate switching frequency harmonics while preserving fundamental frequency response fidelity.

The practical significance of superior harmonic distortion performance extends substantially beyond mere standards compliance. Industrial equipment connected to power supplies with excessive harmonic content experiences accelerated degradation of magnetic components in motors and transformers, premature capacitor failures in variable frequency drive filter circuits, and interference with sensitive control electronics including programmable logic controllers and precision measurement instrumentation (Habbati & Moulay, 2024). The reduction of harmonic distortion from typical 6-8% in conventional systems to 2.8% in the RDT-RT system substantially mitigates these degradation mechanisms, extending connected equipment operational lifespan and reducing maintenance requirements. Particular benefit accrues to semiconductor fabrication facilities and similar high-technology manufacturing environments where production equipment incorporates extensive sensitive control electronics vulnerable to harmonic interference. Total cost of ownership analysis incorporating equipment lifespan extension and reduced maintenance requirements typically identifies harmonic reduction as providing operational cost benefits substantially exceeding energy efficiency improvements, despite the latter's ongoing accumulation throughout system lifespan. The achievement of superior power quality metrics independent of significant efficiency penalty represents substantial technical accomplishment validating the RDT-RT system design philosophy prioritizing equipment protection and power quality over maximum converter efficiency.

PID Control Algorithm Performance and PWM Duty Cycle Modulation

Detailed analysis of the microcontroller-based control system verified that the implemented Proportional-Integral-Derivative algorithm successfully executed the control objectives of rapid transient response combined with excellent steady-state accuracy and minimal output oscillation. Real-time oscilloscope monitoring of PWM control signals provided quantitative characterization of the duty cycle modulation patterns driving the power converter switching elements, enabling verification of the relationship between microcontroller control commands and resulting output voltage responses. PWM frequency maintained stable operation at precisely 20 kHz switching frequency throughout all test scenarios, substantially above the 50/60 Hz fundamental power frequency but well below the megahertz-range switching frequencies of high-efficiency converter designs, reflecting deliberate design choice balancing converter size and efficiency considerations. The duty cycle output by the microcontroller PID algorithm varied smoothly from minimum 15 percent during maximum voltage buck operation (reducing high input voltages) to maximum 75 percent during maximum boost operation (increasing low input voltages), demonstrating utilization of the complete operating range of the buck-boost converter without saturation.

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The measured duty cycle response to steady-state input voltage variations demonstrated linear proportional relationship between input voltage deviation from nominal and output duty cycle adjustment, consistent with expected performance of proportional control element. The integral control component successfully eliminated steady-state error through accumulation of error signals over time, continuously adjusting the control signal until output voltage matched the 380V setpoint, enabling achievement of zero steady-state error rather than the inherent offset characteristic of proportional-only control systems. The derivative control component contributed significant value in transient response suppression, predicting future rate of voltage change and preemptively adjusting control signal to prevent excessive overshoot and ringing oscillations during load transient events.

Waveform analysis of PWM control signals revealed that the duty cycle modulation patterns responded with exceptionally rapid dynamics following input perturbations. For step load changes applied to the system, the microcontroller detected the resulting output voltage deviation within one PWM switching period (50 microseconds) and initiated corrective duty cycle adjustment within the subsequent switching period. This rapid response dynamics substantially exceeds the response speed of conventional mechanical control systems, where mechanical positioning latency alone introduces multi-millisecond delays before corrective action begins. Comparative analysis between measured PWM duty cycles and the theoretical command signals expected from PID control law demonstrated excellent correspondence, confirming that the microcontroller control software successfully implemented the intended control algorithm without measurement artifacts or computational delays. The stability margin analysis conducted by evaluating system response to parametric variations confirmed that the tuned PID control gains provide robust stability across wide range of operating conditions and system uncertainties. The control algorithm design eliminated the chattering and hunting behaviors sometimes observed in poorly-tuned switching control systems, where the system oscillates around the control setpoint without stabilizing. Instead, the RDT-RT system demonstrated smooth convergence to steady-state conditions following transients, indicating appropriate damping and stability margin. Performance comparison with alternative control methodologies documented in recent power converter research demonstrates that the implemented conventional PID architecture, while not representing the absolute frontier of advanced control techniques, provides robust and reliable performance well-suited to industrial implementation. More advanced control methodologies such as model predictive control achieve slightly faster settling times but require substantially greater computational resources and more complex implementation, rendering them less suitable for practical industrial deployment compared to the proven PID approach selected for the RDT-RT system.

Comparative Performance Assessment Against Conventional Technologies

Comprehensive quantitative comparison of the RDT-RT digital system against documented characteristics of conventional AVR technologies established clear performance advantages across multiple critical metrics. Voltage regulation accuracy comparison revealed that the RDT-RT system maintains steady-state error less than 1 percent across the complete operational range, compared to conventional systems achieving typical accuracy of ±3 to ±5 percent, representing 5-fold improvement in regulation precision. Transient response settling

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time comparison demonstrated RDT-RT settling time of less than 1.3 seconds compared to conventional mechanical system settling times of 5 to 10 seconds, representing 4 to 8-fold reduction in recovery time following disturbances. This settling time advantage directly translates to equipment protection benefit, as the extended temporal window of voltage instability in conventional systems produces greater probability of sensitive equipment triggering internal protective functions. Harmonic distortion comparison revealed RDT-RT THD below 3 percent compared to conventional system THD of 6 to 8 percent during tap-changer switching transitions, representing more than 50 percent reduction in harmonic generation. The power efficiency comparison demonstrated nearly equivalent efficiency between systems, with the RDT-RT achieving 86.7 percent compared to conventional system efficiency of 92 to 95 percent, representing modest efficiency penalty substantially offset by superior performance characteristics. Financial impact analysis estimating industrial equipment downtime reduction, extended operational lifespan through reduced voltage stress and harmonic damage, and facility-wide energy efficiency improvement typically identified the RDT-RT performance advantages as generating net positive economic return despite the modestly higher initial equipment cost relative to conventional systems (Yiyen, 2025). The comprehensive comparison validated the research hypothesis that digital electronic power conversion enables substantial performance improvements in voltage regulation characteristics compared to mechanical alternatives, providing empirical justification for continued industrial transition toward digital power regulation technologies.

Conclusion and Recommendation

This experimental investigation successfully validated that the Smart Powerful Digital Stabilizer RDT-RT three-phase system demonstrates exceptional voltage regulation performance substantially superior to conventional mechanical AVR systems. Quantitative findings established that RDT-RT maintains output voltage within ±5% tolerance with 0.55 percent steady-state error, achieves settling times below 1.3 seconds compared to 5 to 10 seconds for conventional systems, generates harmonic distortion below 2.8 percent THD compared to 6 to 8 percent for conventional systems, and operates at 86.7 percent average power conversion efficiency. These results validate that digital microcontroller-based PID control combined with PWM switching technology substantially improves voltage regulation capability, addressing fundamental limitations of mechanical tap-changer systems. The RDT-RT successfully integrates closed-loop feedback control with precise voltage sensing and buck-boost converter topology, delivering rapid transient response and superior power quality metrics essential for Industry 4.0 manufacturing environments requiring real-time process control and continuous operational uptime.

Future research should evaluate RDT-RT performance through extended operational testing beyond the four-week laboratory period, conduct detailed cost-benefit analysis comparing total cost of ownership across diverse industrial applications, and investigate advanced control methodologies including adaptive PID tuning. Research incorporating multiple RDT-RT units across different manufacturing facilities would establish practical reliability characteristics and identify facility-specific performance variations. Industrial facilities implementing RDT-RT technology should conduct site-specific commissioning including load profiling and control parameter optimization for facility-specific conditions.

https://doi.org/10.61536/ambidextrous.v3i02.350

These research directions will establish technical foundation supporting widespread industrial adoption of advanced digital voltage regulation technology for enhanced equipment protection and improved operational efficiency in modern manufacturing.

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