

DESIGN AND PROBABILISTIC PERFORMANCE EVALUATION OF A MICROCONTROLLER-BASED AUTOMATIC VOLTAGE REGULATOR WITH WIDE INPUT RANGE FOR NIGERIAN SUPPLY CONDITIONS

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Abstract: Sensitive equipment across Nigeria routinely receives mains voltage far outside the statutory band, with prolonged undervoltage of 150 to 200 volts interspersed with sags and swells, and commercial regulators with narrow correction windows respond by disconnecting the load much of the time. This paper presents a relay-tap automatic voltage regulator built on a low-cost eight-bit microcontroller, correcting inputs of 110 to 260 volts to 230 volts within plus or minus 7.4 percent. A geometric band design shows that six autotransformer taps are the minimum that cover the full input range at this tolerance, with closed-form relations for tap count, ratios and output bounds that rescale the plan to any specification. True root-mean-square sensing through a 155 to 1 biased divider with a 530 hertz anti-aliasing pole, three volt hysteresis and zero-crossing relay actuation give a worst-case correction latency of 59 milliseconds, under three mains cycles. A two hundred thousand sample probabilistic evaluation against a stylised Nigerian supply scenario finds the design holds the load within the 230 volt plus or minus 10 percent utilisation band for 99.0 percent of samples, against 89.0 percent for a typical commercial unit spanning 160 to 250 volts and 45.9 percent for the raw supply. Non-ideal allowances are budgeted: a 3 percent transformer regulation limit keeps the full-load output inside the band, efficiency runs 97.6 to 99.7 percent, and a bill of materials near 19000 naira positions the design between imported relay regulators and servo machines. All parameters are stated in full for exact reproduction.

Keywords: Voltage regulator, Voltage stabiliser, Microcontroller, Power quality, Wide input range, Nigeria

Nomenclature: AVR, automatic voltage regulator; MOV, metal oxide varistor; RMS, root mean square; SMPS, switched-mode power supply.

1.0 INTRODUCTION

The Nigerian distribution network delivers some of the most disturbed low-voltage supply recorded for any large economy. Chronic generation shortfall and overloaded feeders produce sustained undervoltage, while switching operations, load rejection and network faults add sags and swells on top of it, in the sense classified by IEEE Standard 1159 (IEEE, 2019; Aliyu et al., 2013; Oyedepo, 2012). Surveys of Nigerian firms document the adaptive costs of this supply (Adenikinju, 2003), and outage burdens of the same character are reported across sub-Saharan Africa (Farquharson et al., 2018). The distribution code requires supply at the low-voltage terminal to remain within a few percent of nominal (Nigerian Electricity Regulatory Commission, 2014), yet households and small enterprises commonly measure between 150 and 200 volts for hours at a time. The consequences for connected

equipment are well documented in the power quality literature: motor overheating and stalling under sustained undervoltage, control dropout during sags, and insulation and power supply stress during swells (Bollen, 2000; Dugan et al., 2012; Sankaran, 2002).

The Nigerian market answer is the automatic voltage regulator (AVR), marketed locally as the voltage stabiliser and used here for the mains conditioning device, distinct from the generator excitation regulator of power system practice: a relay-switched autotransformer that boosts or bucks the incoming supply toward nominal. Millions are installed, but the common imported units carry two design compromises that matter locally. First, their correction windows are narrow, typically 160 to 250 volts; below the window the unit disconnects, so in exactly the deep-undervoltage conditions for which Nigerians buy regulators, the device protects by depriving. Second, their analogue comparator control offers coarse bands, fixed hysteresis and no supervisory intelligence such as event logging or soft restart delays for compressor loads. A microcontroller replaces the analogue chain at negligible cost while adding true root-mean-square measurement, programmable hysteresis, zero-crossing switching and protective supervision (Mohan et al., 2003).

This paper contributes a complete, reproducible design rather than another prototype description. Its contributions are fourfold. First, the tap plan is derived rather than asserted: closed-form relations give the minimum number of autotransformer taps, their ratios and the resulting output tolerance for any specified input range, and show that six taps cover 110 to 260 volts at plus or minus 7.4 percent. Second, the sensing, hysteresis and zero-crossing switching chain is designed and its worst-case correction latency budgeted at 59 milliseconds. Third, performance is evaluated probabilistically against a stated supply scenario spanning reported Nigerian conditions, quantifying the compliance advantage of the wide window over a typical commercial unit. Fourth, an indicative cost analysis positions the design in the local market. The study is analytical and design-stage: no laboratory prototype measurements are reported, and bench characterisation is identified as the immediate next step.

2.0 MATERIALS AND METHODS

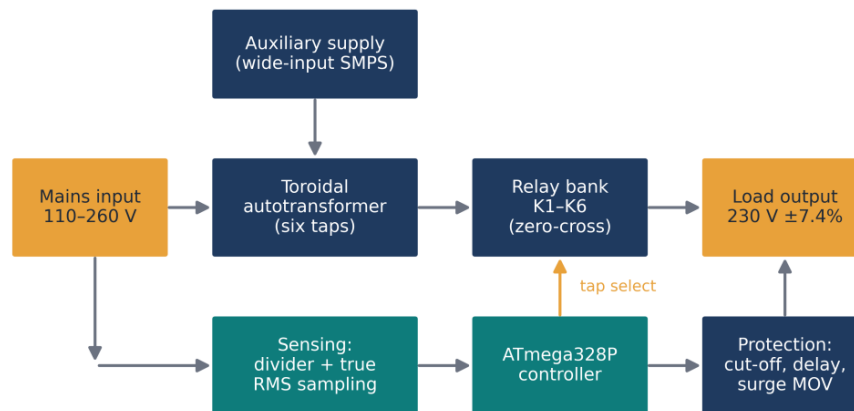
System Architecture

Fig. 1 shows the architecture. The power path is a toroidal autotransformer whose six taps are selected by a relay bank under microcontroller control; the control path senses the input through a precision divider into the analogue converter of an ATmega328P, which computes true root-mean-square voltage, selects the correction band, and drives the relays through zero-crossing synchronised sequences. A wide-input switched-mode auxiliary supply keeps the controller alive across the whole

110 to 260 volt window and below it, so the unit can observe and recover from conditions in which it has protectively disconnected the load. A metal oxide varistor and fuse provide surge and fault protection, and the firmware adds a programmable restart delay for refrigeration loads

Figure 1

System Architecture of the Regulator



Tap Plan Design

The central design question is how many taps are needed. Let the input range be $V_{\min}$ to $V_{\max}$ and let successive band boundaries advance by a constant ratio, so that every band is corrected to nominal by its own transformation ratio. With N geometric bands the step ratio is

$$k = (V_{\max} / V_{\min})^{1/N} \quad (1)$$

and, because each band is centred on the geometric mean of its edges, the output stays within a symmetric relative tolerance

$$\varepsilon = \sqrt{k} - 1 \quad (2)$$

Inverting equation (2) gives the minimum band count for a specified tolerance,

$$N = \ln(V_{\max} / V_{\min}) / \ln[(1 + \varepsilon)^2] \quad (3)$$

For 110 to 260 volts the coverage ratio is 2.36. Equation (3) shows five bands would leave a 9.0 percent tolerance while six bands achieve 7.4 percent, comfortably inside the 10 percent utilisation window that supply standards regard as acceptable at the point of use (IEC, 2009; CENELEC, 2010), so N of 6 is adopted. Each band i spanning edges V_i to V_{i+1} is corrected by the ratio

$$r_i = V_{\text{out}} / \sqrt{V_i \cdot V_{i+1}} \quad (4)$$

Table 1 gives the resulting plan. Every band delivers an identical output window of 214.1 to 247.1 volts, that is minus 6.9 to plus 7.4 percent about the 230 volt nominal, and the sixth band bucks rather than boosts. Fig. 2 draws the complete transfer characteristic, including the plus or minus 3 volt hysteresis applied at each boundary to prevent relay chatter when the supply dwells near a threshold, and the protective cut-off regions outside the design window.

Table 1

Six-Band Tap Plan (Input 110 to 260 V, Output 230 V Nominal)

Band	Input window (V)	Transformation ratio	Output window (V)
1	110.0 to 127.0	1.946	214.1 to 247.1
2	127.0 to 146.5	1.686	214.1 to 247.1
3	146.5 to 169.1	1.461	214.1 to 247.1
4	169.1 to 195.2	1.266	214.1 to 247.1
5	195.2 to 225.3	1.097	214.1 to 247.1
6	225.3 to 260.0	0.950	214.1 to 247.1

Figure 2

Transfer Characteristic With Hysteresis and Cut-Off Regions

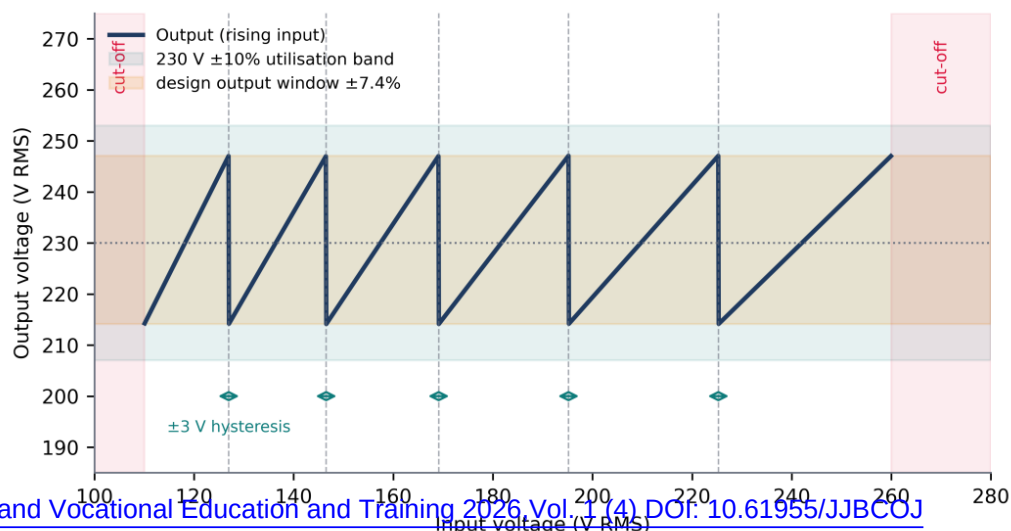
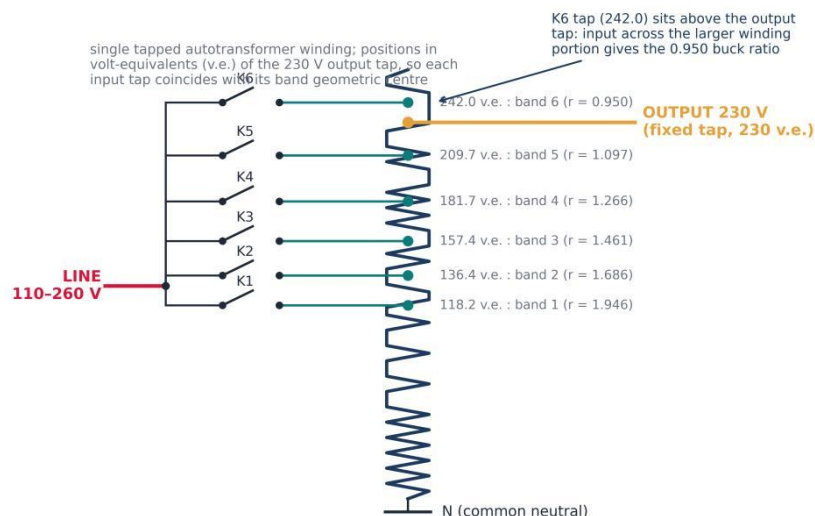


Fig. 3 shows how the plan is realised on a single tapped winding, and answers the natural question of how one autotransformer both boosts and bucks. The 230 volt output is taken from a fixed tap, the neutral is common, and the relay bank applies the line to one of six input taps. Expressed in volt-equivalents of the 230 volt output tap, each input tap coincides exactly with the geometric centre of its band from Table 1: 118.2, 136.4, 157.4, 181.7, 209.7 and 242.0. Each ratio is simply the turns ratio between the fixed output tap and the selected input tap; the sixth input tap, at 242.0, sits above the output tap, so the input is applied across the larger winding portion and the 0.950 buck ratio follows without any reversed or auxiliary winding.

Figure 3

Autotransformer Tap Arrangement: Fixed Output Tap, Relay-Selected Input Taps, Buck Achieved by the Top Tap



Sensing, Control and Switching

The controller samples the attenuated input waveform at 2 kHz and computes true root-mean-square voltage over a two-cycle window,

$$V_{rms} = \sqrt{[(1/n) \sum v_j^2]} \quad (5)$$

with n of 80 samples taken at 2 kHz across the 40 millisecond window at 50 Hz. True root-mean-square measurement matters because the Nigerian waveform is frequently distorted by generator back-feed and non-linear loads, conditions under which average-responding measurement misreads by several percent (Sankaran, 2002). Zero crossings are detected in hardware by a bidirectional optocoupler of the H11AA1 class driven from the sensing divider, whose pulse train feeds an interrupt pin, with a software fallback that detects the sign change of consecutive samples should the detector fail. Band selection applies the Table 1 boundaries with plus or minus 3 volt hysteresis. When a band

change is required, the firmware waits for the next zero crossing, opens the outgoing relay, enforces a 4 millisecond break-before-make gap so that two taps are never bridged, and closes the incoming relay, a sequence that minimises contact arcing and inrush (Mohan et al., 2003; Slade, 2014). A resistor-capacitor snubber of 100 ohms and 100 nanofarads in a class-X2 capacitor is fitted across each contact set to absorb the residual interruption transient, complementing the varistor across the load. After any protective cut-off, restart is delayed by a default 180 seconds, configurable from zero to 300 seconds, with a random jitter of plus or minus 10 seconds so that neighbouring units do not restart their compressor loads in unison after an area outage. Fig. 5 gives the firmware state machine, including the protective cut-off applied whenever the input leaves the design window or the output leaves its bounds for more than 200 milliseconds.

Fig. 4 gives the input protection and sensing circuit at component level. After the fuse, a 320 volt varistor, whose 14 millimetre disc class absorbs transient energy of the order of 150 to 200 joules and can be paralleled or upsized to a 20 millimetre disc for severe lightning exposure, and a common-mode filter, the line feeds a 155 to 1 precision divider of 1 megaohm against 6.49 kilohms, which places the 260 volt worst-case peak at 2.37 volts. The divided waveform is capacitively coupled onto a 2.5 volt mid-rail bias formed by an equal 100 kilohm pair, so both half-cycles reach the converter and the signal occupies 0.13 to 4.87 volts of the 5 volt range. An anti-aliasing pole at about 530 hertz, set by a 33 nanofarad capacitor against the roughly 9 kilohm upstream impedance, suits the 2 kHz sampling while retaining the harmonics that motivate true root-mean-square measurement, and a dual Schottky pair clamps the pin to the rails. The controller common is referenced to neutral at a single star point, so the assembly is not isolated and presents no user-accessible signal connections.

Figure 4

Input Protection and Voltage Sensing Circuit: Divider, Bias, Anti-Aliasing, Clamp and Zero-Cross Detection

Firmware Control Loop

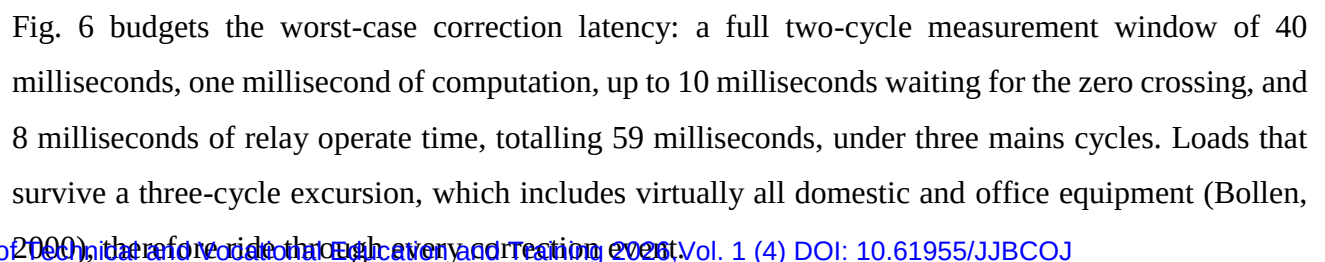
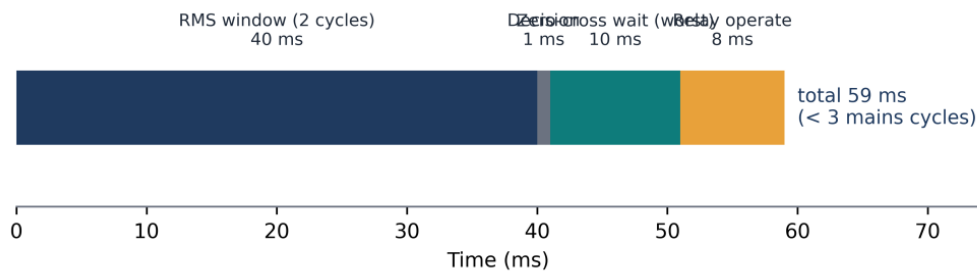


Figure 6

Worst-Case Correction Latency Budget



Component Selection and Indicative Cost

Table 2 lists the principal components with the selection rationale. The ATmega328P was chosen over more capable controllers because the task needs one analogue channel, six outputs and modest arithmetic (Microchip Technology, 2020), and the part is ubiquitous and serviceable in Nigerian markets; the autotransformer is specified toroidal for regulation and acoustic reasons at a one kilovolt-ampere design load; and the relays are 30 ampere types operated at a fraction of rating for contact life; all returns, including the auxiliary supply and the sensing common, meet at the single neutral-referenced star point annotated in Fig. 4; core and winding sizing for the one kilovolt-ampere rating follows standard transformer design practice (Flanagan, 1993). The indicative bill of materials totals about 19000 naira at prevailing component prices, which positions the design between imported relay regulators of narrower window and servo-motor machines of several times the cost.

Table 2

Principal Components and Indicative Costs (Single-Unit, Prices Indicative at the Time of Writing)

Component	Selection	Indicative cost (naira)
Controller	ATmega328P, internal 8 MHz	1200
Autotransformer	1 kVA toroidal, six taps	9500
Relay bank	6 × 30 A, 12 V coil	3600

Sensing and zero-cross	155:1 divider, bias, filters, BAT54S, H11AA1	900
Auxiliary supply	Wide-input 12 V/5 V SMPS module	1500
Protection	MOV, fuse, thermal cut-out	800
Contact snubbers	$6 \times RC$, 100 Ω + 100 nF class X2	300
Enclosure and wiring	Steel case, terminals, indicators	1200

Probabilistic Evaluation Method

Rather than quote performance at a handful of spot voltages, the design is evaluated against a stylised supply scenario spanning reported Nigerian conditions: a mixture in which chronic undervoltage centred on 195 volts carries 55 percent of the probability, near-nominal supply centred on 225 volts carries 30 percent, deep sags centred on 150 volts carry 10 percent and swells centred on 250 volts carry 5 percent, truncated to 100 to 280 volts. The scenario is a stated modelling assumption in the spirit of the sag and swell phenomenology of Bollen (2000), not a measured feeder record, and the evaluation is repeated identically for this design and for a reference unit with the typical commercial window of 160 to 250 volts and four internal bands. Two hundred thousand input samples are drawn, each unit maps them through its transfer characteristic with protective cut-off outside its window, and compliance is scored as the share of samples delivered within the 230 volt plus or minus 10 percent utilisation band, with disconnection counted as non-compliance since a disconnected load is served no better than a damaged one.

Non-Ideal Allowances: Regulation, Efficiency and Thermal Design

Three departures from the ideal transformer are budgeted explicitly. Regulation: a toroidal autotransformer of this class holds regulation near 3 percent at rated load, and applying the full 3 percent droop to the worst band edge moves the minimum output from 214.1 to 207.7 volts, minus 9.7 percent, still inside the 10 percent utilisation band though with only 0.7 volts of margin. The design specification therefore requires transformer regulation not exceeding 3 percent at the one kilovolt-ampere rating; a core achieving only 4 percent would require derating to roughly 750 volt-amperes. Repeating the probabilistic evaluation of Section 2.5 with the full-load droop applied leaves compliance unchanged at 99.0 percent, since the droop consumes margin rather than crossing the band

edge. Efficiency: an autotransformer transforms only the differential volt-amperes, a fraction equal to the magnitude of one minus the reciprocal ratio. Composite copper and core losses of small toroidal transformers at rated load typically run 3 to 6 percent of the processed volt-amperes (Flanagan, 1993), so with a mid-range 5 percent loss assigned to the transformed power the estimated efficiency runs from 97.6 percent in the deepest boost band to 99.7 percent in the buck band, well above isolation-transformer alternatives (Flanagan, 1993). Thermal: the worst continuous dissipation is about 24 watts, in band 1 at rated load, falling below 12 watts across the bands the scenario occupies most; a louvered steel enclosure provides ample natural convection for this dissipation at the 40 degree Celsius ambients of the region, with the thermal cut-out of Table 2 guarding the abnormal case. Contact life is estimated on a stated duty assumption: a badly disturbed feeder producing 200 band changes per day gives the busiest relay about 30000 operations per year, and with zero-crossing switching and snubbing holding contact stress well below rating (Slade, 2014), an electrical life of 300000 operations implies a relay service interval near ten years, comfortably beyond the transformer and enclosure life expectations.

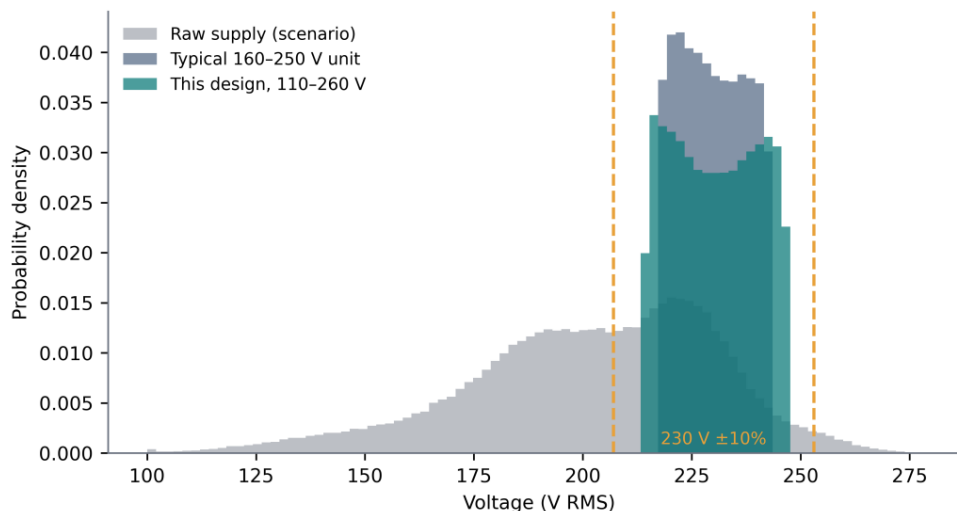
3. RESULTS AND DISCUSSION

Regulation and Compliance

Fig. 7 overlays the voltage distributions. The raw scenario supply lies within the utilisation band for only 45.9 percent of samples, confirming that the stylised mixture indeed represents a badly disturbed feeder. The commercial reference unit lifts compliance to 89.0 percent, but its narrow window forces protective disconnection for 11.0 percent of the time, almost all of it during the deep undervoltage episodes that motivate regulator ownership in the first place. The wide-window design delivers 99.0 percent compliance with only 1.0 percent disconnection, confined to excursions beyond 110 or 260 volts where disconnection is the correct protective response. The tenfold reduction in load deprivation, from 11 percent of the time to 1 percent, is the practical payoff of the two extra boost bands, and it is bought with two additional relays and transformer taps rather than with any exotic component.

Figure 7

Voltage Distributions Under the Supply Scenario: Raw Supply, Commercial Reference Unit and This Design



Sensitivity of the Result

The compliance advantage is not an artefact of the particular mixture weights. Because the reference unit disconnects below 160 volts while this design corrects down to 110 volts, the gap between the two units equals the probability mass lying between those voltages plus the reference unit's own tolerance shortfall; any scenario that places meaningful probability below 160 volts reproduces the ordering, and scenarios that place more, as feeders at the end of long rural lines in Kebbi State plausibly do, widen it. Conversely, on a healthy urban feeder confined to 200 to 240 volts the two units perform identically, which is exactly the circumstance in which no regulator earns its keep. The design tolerance itself responds only to the band count through equation (2): a seven-band variant would tighten the output window to plus or minus 6.3 percent at the cost of one further relay and tap, a straightforward commercial option the closed-form plan makes easy to cost.

Practical Implications

Three implications follow for local practice. For manufacturers and repair workshops, the closed-form tap plan converts regulator design from copying imported units into a two-line calculation, and the derived plan can be wound onto locally available toroidal cores. For buyers, the analysis quantifies what the narrow AVR window costs: a household on a chronically depressed feeder spends roughly one hour in ten disconnected by a typical imported unit, a figure the wide design reduces tenfold. For the microcontroller platform, the marginal additions the analogue chain cannot offer, true root-mean-square sensing, programmable restart delay, event logging through the serial port, come free once the controller is present, and the logged band-occupancy record doubles as a feeder-quality survey instrument for the distribution company.

Four limitations bound the claims. First, the study is analytical: the transfer characteristic, latency budget and compliance figures follow from the stated design relations and scenario rather than from bench measurements, and prototype characterisation covering regulation under load, relay contact behaviour at switching, thermal performance of the transformer and measured latency is the planned next step. Second, the supply scenario is stylised; logging campaigns on real Kebbi feeders would replace the assumed mixture with measured statistics and are a natural companion study; relatedly, the evaluation draws independent samples and therefore measures time-share compliance rather than temporal dynamics, with boundary dwell handled by the hysteresis design and switching frequency by the stated duty assumption of the contact life estimate. Third, the regulation, efficiency and thermal allowances of Section 2.6 are budgetary estimates from standard transformer practice, and bench work must confirm that a locally wound toroid meets the 3 percent regulation the tolerance analysis requires. Fourth, costs are indicative single-unit component prices excluding labour and enclosure fabrication economics at production quantity.

4.0 CONCLUSION

This paper has presented the complete design of a microcontroller-based automatic voltage regulator correcting any input between 110 and 260 volts to 230 volts within plus or minus 7.4 percent. Closed-form relations for band count, tap ratios and output tolerance were derived and yield a six-band geometric plan; true root-mean-square sensing, programmable hysteresis and zero-crossing relay sequencing bound the worst-case correction latency at 59 milliseconds; and a two hundred thousand sample probabilistic evaluation under a stated Nigerian supply scenario finds 99.0 percent compliance with the utilisation band against 89.0 percent for a typical commercial unit and 45.9 percent for the raw supply, with load disconnection reduced tenfold. The indicative bill of materials of about 19000 naira, with budgeted efficiency of 97.6 to 99.7 percent and a 3 percent regulation specification, makes the design manufacturable locally from ubiquitous parts. Bench characterisation of a prototype and a feeder-logging campaign to replace the stylised scenario with measured Kebbi State statistics are the planned next stages of the work.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this paper

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