Power Supply Quality Improvement With An Extended Range Domestic Voltage Requlators

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Abstract: One of the effects of the rapid expansion of distribution networks in Nigeria is that the service voltage of many consumers lies outside the stipulated tolerance. This problem has been addressed by the use of commercial, domestic voltage regulators that typically work between 150 and 250 V. Unfortunately the service voltage experienced by many consumers lie well outside this range. In order to establish the operating range of suitable regulators, a preliminary study of the voltage supply in Ondo State, Akure as a case study, the distribution network was carried out. It revealed that up to 30% of consumers receive voltages of less than 80V whilst up to 50% receive less than 120V. In the light of this, it was decided to design a suitable voltage regulator rated at 1.5KVA having an input voltage range between 50V and 250V with an expected nominal output voltage of 220V±6%.A theoretical framework was developed for the general class of switched electronic AC Voltage regulators using EXCEL®. It provides a mechanism for computing the number and ratings of tapping needed to regulator transformers once the output voltage tolerance is specified.

Index Terms: Distribution Network, regulator, transformer, tapping, voltage tolerance.

1 INTRODUCTION

THE problems encountered by consumers in the Nigerian power supply system are numerous. However, a major problem is the quality of power supplied. The availability of adequate supplies of electricity at the nominal level of 220 volts for domestic purposes is a matter of great concern throughout Nigeria. In the pre – oil boom era the quality of power as characterized by the supply voltage closely matched the nominal values. However the boom led to a phenomenal growth of demand in power which was met by crash supplies of expansion of the distribution lines often times without the commensurate upgrading of the supply transformers. In some cases larger transformers were installed to feed loads located further and further away from the sub – station (Olufeagba, 2006). The net result of this is that consumers in different parts of an area receive voltages far removed from the nominal values. Consequently a burgeoning market for automatic stabilizers and regulators rated between 0.5 KVA and 10 KVA for the domestic market has grown. The devices have various advertised performance limitations and employ a combination of electronics to select the tappings on transformers. In an ideal situation, voltages no less than 170 volts can be readily taken care of with outputs lying within the stipulated tolerance of the supply authority's values. Unfortunately, the unrestricted expansion of the distribution networks has led to extremely low voltages so that the typical commercially available voltage regulators are not effective for restoring some sort of acceptable operating voltage. A preliminary study carried out during this research and reported below, reveals that the situation in practice is much worse with consumer voltages as low as 50 volts being quite possible (Olufeagba, 2006). Statistical data reveal that 22% of stabilizers purchased by consumers did not perform satisfactorily when the input supply voltage was less than 160 volts. Products like Qlinks, Binatone, Philips, Super Masters, Century etc, regulate input voltage that falls within 160 volts and 260 volts, a range that does not cater for the Nigerian buyer (Ogunlade, 1999).

2.1. The Objectives of the Research

The objectives of this research are as follows:

- **i.** To determine the range of the voltages supplied to consumers in the electric power distribution network;
- **ii.** To design a suitable voltage regulator rated at 1.5 KVA with the output voltage of 220±6% volts, when the input voltage varying between 50 volts and 250 volts.
- **iii.** To evaluate the performance of the designed voltage regulator.

2.2 Scope of the Research

The supply voltage experienced by the consumers in the Akure network was monitored at several parts of the network and the range of values established. The experience of users of commercial voltage regulators was assessed and confirmed theoretically. The parameters of voltage regulators that can improve the quality of service were then determined. A procedure for the design of the control transformer in a.c. Voltage regulators using a generic formula to determine the toppings were simulated and verified using EXCEL® software. The decision circuit of the regulator was designed using an iterated logic technique.

2.3. Research Methodology.

The design of the regulatory system depends mainly on the power requirements, the input voltage range, the nominal output voltage and regulation. These requirements need to be translated into design specifications for the output element which in this case is a multi-tapped transformer. The method employed in this research is based on tap-changing of a special regulator transformer.

3. The Automatic Voltage Regulator (AVR)

The ideal automatic voltage regulator is a device which uses a switched autotransformer to maintain an AC output that is as close to the standard or normal mains voltage as possible, under conditions of fluctuation (Boylestad, 2007). It uses a servomotor (or negative feedback) to control the position of the tap (or wiper) of the autotransformer. An increase in the mains voltage causes the output to increase, which in turn causes the tap (or wiper) to move in the direction that reduces the output towards the nominal voltage (Patchet, 1954). With the exception of passive shunt regulators, all modern electronic voltage regulators operate by comparing the actual output voltage to some internal fixed reference voltage. Any difference is amplified and used to control the regulation element in such a way as to reduce the voltage error. This forms a negative feedback servo control loop; increasing the open-loop gain tends to increase regulation accuracy, but reduce stability (avoidance of oscillation, or ringing during step changes). There will also be a trade-off between stability and the speed of the response to changes. If the output voltage is too low (perhaps due to input voltage reducing or load current increasing), the regulation element is commanded, up to a point, to produce a higher output voltage - by dropping less of the input voltage (for linear series regulators and buck switching regulators), or to draw input current for longer periods (boost-type switching regulators); if the output voltage is too high, the regulation element will normally be commanded to produce a lower voltage. However, many regulators have over-current protection, so entirely stop sourcing current (or limit the current in some way) if the output current is too high, and some regulators may also shut down if the input voltage is outside a given range (Sen, 1987). While there are alternating and direct current regulators, this work involves the former type. The AVRs used in Nigeria are mostly of the domestic variety and perform the function of maintaining the output voltage at 220 volts ± 6%. Voltage regulators are to be found in all power stations starting with the voltage regulators used in the large turbo-alternators that supply the grid or in captive power stations. Those ones use some sequence filters to select the sample of the output voltage developed, amplify it electronically and use the resulting output to drive the field of a pilot exciter or the main exciter which then adjusts the field of the main alternator to ensure that the voltage fed to the bus is nearly as constant as possible (Steward, 1995). Automatic voltage regulators consist of two units: the measuring unit and the regulating unit. The function of the measuring unit is that of detecting a change in the input or output voltage of the automatic voltage regulator and producing a signal to operate the regulating unit. The purpose of the regulating unit is that of acting, under the signal from the measuring unit, in such a manner as to correct the output voltage of the regulator to, as near as possible, a constant or the predetermined value (Patchet, 1954). Voltage regulators are essentially auto-transformers, with the secondary (or series) portion of the coil arranged so that all or part of its induced voltage can be added to or subtracted from the line or incoming primary voltage (across which the primary or exciting portion of the winding is connected). The voltage variations are accomplished by changing the ratio of transformation automatically without denergizing the unit (Pansini, 1983).

3.1. Basic Structure of Commercial Voltage Regulators

Basically, the AVR consists of the transformer section, the control section and a protective component (unit) -the fuse that will blow off if excess current flows into the unit. The function of the transformer is to produce the required output voltage, about 220 volts, with the help of the control unit (Gupta and Lyman, 1980). The control circuit section consists of the rectifier unit, the comparator, the control unit and the switching unit. The rectifier unit produces the rectified DC voltage (half-wave rectification) to energize the switching components such as relays and transistors used in the control unit. The function of the relays is to select (switch ON) the appropriate terminal in the transformer unit while the transistors act as switches for the relays. After comparing the input and output voltages through the feedback stage, a signal will be sent to the switching device (transistor) and the relays to switch ON in the presence of any abnormal voltage. The comparator stage compares the output with the input (I. e. 220 volts) reference voltage, which is not stable. Any change or difference will cause a signal to be sent to the switching unit for proper selection (Paraskevopoulos, 2002).

3.2Basic Structure of the Extended Range Domestic Voltage Regulators.

In the figure 2.2, the output voltage of the pre-regulated section is translated into the main regulator stage by a boost transformer that translates the low voltage into the working range. This arrangement seemed to be more economical and was adopted for the final product. The resulting device has been tested and verified to satisfy the required performance.

3.3. Survey of Supply Voltage in Some Parts of the Akure Distribution Network.

Results from investigations conducted in some areas in Akure reveal that most consumers of electrical energy receive considerably lower voltage from Power Holding Company of Nigeria (PHCN) mains supply than the nominal expected value of 220 volts (6% tolerance. Generally, values of voltages obtained vary as some consumers experienced low voltage in the evening, while some have a fairly good voltage supply late at night. This has prompted many consumers of electricity not to use their electrical equipment for fear of breakdown from incessant voltage fluctuations. It was decided to estimate the extent of the deviation and quantify the supply voltage by sampling the consumer voltage at a number of substations in the Akure metropolis. Table 1.1 shows the selected substations and the nature of the distribution lines they supplied. It is clear from the results that almost all the sub-stations studied feed loads that are many spans from the transformer. The spans range from 1 to 90 with an average of 54 spans. This implies that using an average span length of 50 meters that some loads were being supplied at 4.5 km from the substation. With the average distance being about 2.5 km. This has very serious implications for voltage drop and power loss for both the consumer and the supply authority. As a follow up of the study, the voltages at some points in the network were monitored and recorded. The result of a survey of supply voltage and its distribution for a sample of the substations are shown in the table 1.2.

Table 1.1: Sampled Substations in the Akure Metropolis

Location	Substation	Spans from S/S	Estimated Number of Houses serviced
Jegele/Adedeji-Estate	LA (315kVA)	80 90	100 102
Shagari Village	Redeem Church(500kVA)	60	67
Ireakari Estate	Fagbote (500kVA)	62	73
Abusoro Lay-out, Ijoka	Davog(300kVA)	47	195
Ilotin area off-Ijoka road	Davog(300kVA)	51	188
St.Francis area Gaga, Oke-Aro	Kayode,Jodeb (500kVA)	28	210
Ilesha-Owo Express road	Ehindero(200kVA)	33	91
Ilu-la quarter Oda-road	New Sijuade [300kVA]	15	103

Table 1.2: Typical Supply Voltages at Ends of the Sampled Areas

Location	Typical Voltage at daytime	Typical Voltage at night.
Adedeji Estate, Jegele Village	70V	60V
Shagari Village	60V	50V
Ireakari Estate	70V	50V
Arcade	80V	60V
Abusoro Layout,Ijoka	60V	50V
Ilotin Area off Ijoka Road	80V	70V
St.Francis Area Gaga, Oke-Aro.	90V	60V
Ilesha-Owo Express Road	80V	60V
Ilu-la Quarter ,Oda-Road	120V	130V

It is clear from the above results that the fears expressed by the consumers are real and the standard commercial voltage regulators cannot correct the deficiency in the voltage from the supply. This establishes a strong argument in support of the development of such voltage regulators and indicates that a viable market exists for such devices for the foreseeable future. Indeed, this condition will persist until the distribution practice of the supply authority is amended to reduce the number of spans that can be serviced from one sub-station or some other structural modifications are made (Brown, 2002).

3.4. Design and Analysis of the Electronic Control Circuit.

The electronic control for the extended range regulator consists of:

1. The DC power supply unit.
2. The transformer tap-select unit
3. The protection unit.

The control part of the regulator is a device which can select the correct tapping in the variable turn regulator transformer so as to keep the output voltage within the 6% band. It consists of a set of comparators whose output at any given time determines the choice of the tapping to be energized.

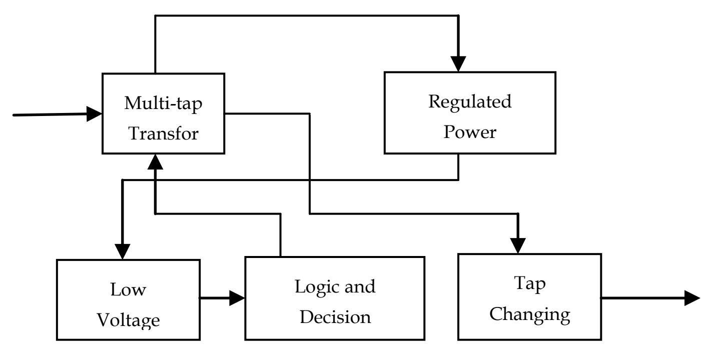

Figure 3.3: Block diagram of control unit for automatic voltage regulator.

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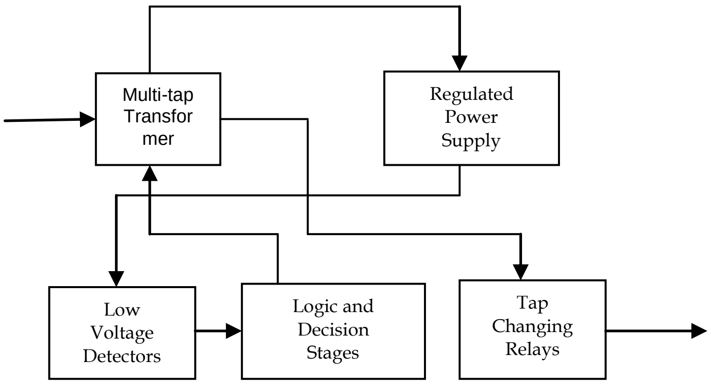


Figure 3.3: Block diagram of control unit for automatic voltage regulator.

Table 3.2: State Table for the Iterative Logic Tap Selector

State	Bk-1	Ak	Ck-1	Ck	Bk.	Wk
S0	0	0	0	0	0	0
S1	0	0	1	0	0	0
S2	0	1	0	Fault	Fault	Fault
S3	0	1	1	1	1	0
S4	1	0	0	Fault	Fault	Fault
S5	1	0	1	Fault	Fault	Fault
S6	1	1	0	1	1	1
S7	1	1	1	1	1	0

The design of these circuits can be very tedious since there are in general many variables. Great simplification can be achieved by noting that each stage can be treated as identical elements and an iterative design adopted (Kohavi, 1970). This approach requires that after each comparator, a signal is developed and used by the $(n+1)^{th}$ stage to return a decision to the initial stage.[1] A closer look would reveal that there is also a need for information from succeeding stages before a correct switching decision can be taken. Consider the k^{th} stage of the iterated circuits bounded on the lower side by the $(k-1)^{th}$ and on the higher side by the $(k+1)^{th}$ stage. The truth table for this system which transmits to succeeding stages the state of its comparator via a signal B_{k-1} and the preceding stage the system condition C_k It can be readily shown that the logic signals may be synthesized as follows:

$$W_k = B_{k-1} A_k C_{k+1}' \quad (3.15)$$

$$B_k. = C_k = (C_{k+1} + B_{k-1}) A_k \quad (3.16)$$

The final signal is vital and it indicates fault conditions as shown in Table 3-2

$$\text{Fault} = [B_{k-1}' A_k C_{k+1}' + B_{k-1} A_k'] \quad (3.17)$$

Where W_k is the switching function for the k^{th} relay
A_k is the output of the k^{th} comparator and
C_k and B_k are condition signals.

Since the overall system has a beginning and an end these must be expressed as initial conditions. For the system above, the initial conditions are:

$$B_0 = 1 \text{ and } C_{N+1} = 0.$$

This technique is particularly suitable for pattern recognition, and encoding and decoding circuits with large number of parallel inputs. Also, circuit specification is simplified and large-variable problems reduced to a more tractable size. Initially, the method was evolved for relay circuitry, but it can be gainfully employed with transistor logic. It should be pointed out that the speed of the circuit is reduced because of the time required for the signals to propagate along the network; the number of interconnections is also considerably increased. In general, iterative design does not necessarily result in a more minimal circuit. It does, however lead to a more flexible circuit, in that the logic system may be extended to handle more external variables by the simple addition of more cells (Lewin, 1974).

4. Results and Discussion

4.1 Testing of the AVR Input and Output Voltages.

The result shown in Table 4.1 represents the test carried out in the AVR.

Table 4.1: AVR Input and Output Voltages

Input Voltage (volts)	Output Voltage (volts)
50	206.9
70	233.2
90	206.9.
100	233.2
130	206.9
160	233.2
190	206.9
200	233.2
220	233.2
230	233.2
250	233.2

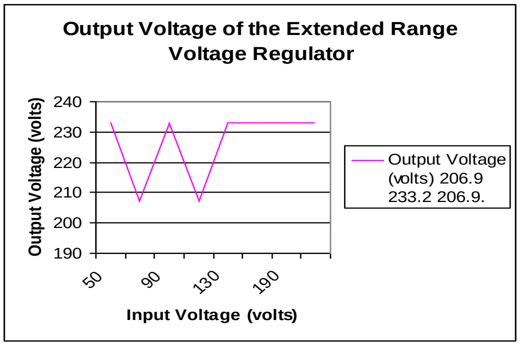
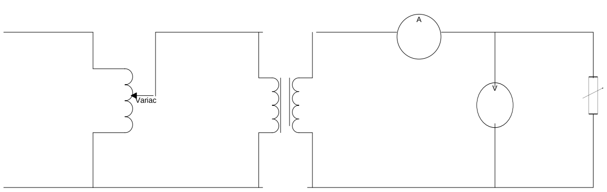


Figure 4.3: Graph of the Extended AVR Input Versus Output Voltages

4.2 Comparative Performance of Voltage Regulators.

In order to establish the results of this work, it was decided to carry out a test of the performance of two commercial voltage regulators and the one developed here. The two commercial regulators were the 1.5kVA Q-link AVR and 1.5kVA Binatone AVR models. The variation of mains supply that will be experienced was simulated by using a Variac. The applied voltage for the test objects was the output of the Variac which was monitored by a multimeter. The variable voltage was distributed to the three test objects through a distribution board. A multimeter was then connected to the output of each device. The rig setup is as shown in figure 4.4 below.



The voltage of the Variac was varied between 50volts and 250 volts. At each stage the outputs of the three regulators were read (almost) simultaneously. The results of the experiment are as shown in Appendix E.Table 5

Vinput(Variac) Input Voltage	Voutput of 1.5kVA Q-link(V)	Voutput of 1.5kVA Binatone(V)	Extended range Output 1.5kVA
50	0	0	206.93
70	0	0	208.34
90	183	174	211.26
100	196	177	214.82
130	198	186	218.78
160	200	187	219.4
190	213	189	220.95
200	219	220	221.71
220	233	220	224.35
230	242	229	228.35
250	249	233	232.23

The results are presented in the graphs of figure 4.5

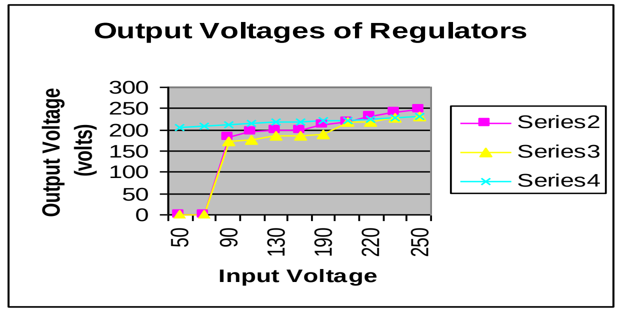


Figure 4.5: Graph of Comparative Performance of Voltage Regulators

The results of all three devices have a similar shape although the exact values differ. It can be seen from the study that the two commercial voltage regulators have knee voltages at about 100 volts and then the output improves slightly as the input voltage increases to 250 volts. The extended range regulator on the other hand has a knee voltage that is below 50 volts confirming the design requirements made earlier. It has a better performance overall since it maintains the output voltage well within the ± 6% band stipulated by the power authorities. From the results, it is clear that the extended range regulator is superior to the commercial regulators. A test was carried out to determine its stability by setting the voltage to the break values of the transformer winding. It was discovered that the behavior in this region could lead to the same type of chatter observed by the commercial ones. The study of the stability properties of voltage regulators is beyond the scope of this work and is noted in passing.

5. Conclusions

Having determined the voltage ranges for various types of supply variations of Akure consumers of electricity, design and construction of extended range domestic voltage regulators of 1.5kVA rating were designed, constructed and tested with the different voltage range (50-250 V) at the input and the output gives the stabilized voltage of 220 volts as required for the satisfactory performance of the project work. The minimum stabilized output voltage is 206.8 volts and the maximum stabilized output voltage is 233.2 volts.

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