Design and Construction of a 10kVA, 220Volts Constant Voltage Transformer for Line Voltage Conditioning

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Abstract: - **This paper presents the Design and Implementation of a Single-Phase, 220 volts, 10kVA, Constant Voltage (ferro-resonant) Transformer for Single-Phase AC Voltage Conditioning. The design approach adopts the use of traditional design calculations and modeling methods for the design and selection of various transformer parameters, as well as peripheral components. Design-specified pre-fabricated, transformers of differing parameters were connected into a non-linear unit to passively provide voltage regulation through ferro-resonance. Through perfect flux limiting, the prototype was able to provide extremely stable voltage regulation, even at relatively high supply frequency swings. Test results for a supply voltage of 220v, at 50Hz (±2%), indicate good output voltage conditioning over a wide range of nominal input voltage variation (±20% or 90 volts approximately). Some salient features of this prototype include; very high reliability due to the absence of semiconductor or moving parts, simplicity of operation due to absence of feedback control, intrinsic current limiting and short circuit protection, energy storage for line loss up to main 3ms at typical load to ensure ride-through capabilities, short-term over load capacity, etc. The research findings provide footprint solutions to the most common Electric Power quality problems at both Utility and Consumer ends.**

Keywords: **power quality, ferroresonance, flux-limiting, current-limiting, voltage-regulation**

I. INTRODUCTION

The Nigerian electricity grid, which is the main source of electrical energy for consumers in Nigeria, is an ailing sector with no remedial destination in sight. Power quality problem is viewed as one of Nigeria's most daunting bottlenecks to economic stability. The problem is not only the near absence of electrical power supply, but the inherent loss of quality in the supplied electrical power [1].The grid as well as the power sector, is characterized by some major debilitating challenges, which include sub-optimal utilization of generation plants (partly due to insufficient gas molecule availability), inadequate transmission infrastructure and high distribution losses [2]. The result is that consumers are perpetually faced with lingering power quality problems ranging from system instability to constant power interruptions. Electric Power Quality (EPQ) is a term that refers to asituation where electricsystem parameters such as distribution bus voltages and currents exhibit a near sinusoidal waveform at rated magnitude and frequency. Voltage sags are among the most significant power quality problems impacting on sensitive industrial and home equipment. Power quality standards define and classify voltage disturbances [3]. Moreover, modern systems in industrial plants are based on high-tech equipment for increased productivity and this requires high quality electrical power. In addition, poor quality electricity can also cause damage to domestic electronic equipment, which more often than not now has large-scale integration of miniature electronic circuits. With the growing popularity of nanotechnology in Nigeria recently, and the attendant need for sustainable electrical power quality, the increasing need to provide additional line conditioning for electrical power at consumer points becomes inevitable. This paper presents an optimized design of a heavy duty ferroresonant (or constant voltage) transformer well suited for the purpose of line conditioning.

A Constant Voltage Transformer (CVT) is a transformer which is basically non-linear, and which provides a regulated voltage output passively (without solid state devices) through ferroresonance (where the term ferroresonant transformer was derived) [4]. Ferroresonance refersto the behavior of iron cores while operating near a point of magnetic saturation, such that the core is so strongly magnetized that further variation in the input voltage has little or no impacton magnetic flux build-up. Basically, the ferroresonant action is more of a flux limiter rather than a voltage regulator. Nonetheless, with a fairly constant supply frequency, the CVT can maintain an almost constant output voltage even as the input voltage varies widely [5]. In fact, for every 1% change in supply frequency, the output voltage of the CVT varies about 1.2% such that even with a considerable deviation in generator frequency (2-Hertz), results in an output voltage change of only 4% or less. In short, CVTs are basically 1:1 transformers that are excited high on their saturation curves, thereby providing an output voltage which is not significantly affected by input voltage variations[4]. This special characteristic is the foundation of the design presented in this paper.

II. KEY OBJECTIVES

To achieve the design and realization of the CVT, the following key objectives would be met; implementation of a ferroresonant circuit to achieve Superior Voltage Regulation. Even with considerable variations in input voltage of up to ±20% of nominal, the output voltage regulation would be about 1% to 4%; the accurate and proper sizing of cores and winding through the use of traditional model equations; and the implementation of a "tank circuit" design to provide a ride-through capability allowing a completely uninterrupted transfer to an alternate source for short durations to avoid transient spikes.

III. THEORY OF OPERATION

The influence of variations in mains voltage and load are reduced to a minimum, owing to the choice of the transformer winding ratio, and thusthe CVT gives better voltage stability. The voltage is taken up by the relatively high series inductance at secondary short circuit, which limits the short circuit current to approximately 2 times nominal current. In the classic transformer parasitic or transient signals can be transmitted between primary and secondary by capacitive coupling and mutual induction. Usually the coils are wound one on top of the other.

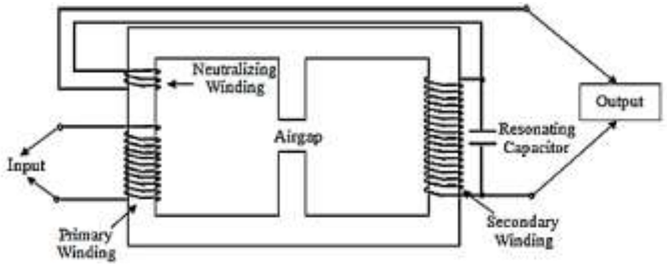


Figure 1. Standard CVT Core Design

A standard CVT core design is as shown in figure 1 above. The standard type of construction brings with it a large mutual induction and significant parasitic capacitance between the two circuits. While the introduction of an electrostatic screen between the coils will reduce the capacitance, there is little that can be done to diminish the mutual inductance between them. In the optimized design, the primary and secondary coils are partly woundon entirely different core members to create a magnetic shunt, which considerably reduces the mutual induction and the parasitic capacitance. The existence of shunts and the saturation of the secondary core further lower the output level of the parasitic signals due to mutual induction. An electrostatic screen interposed between the primary and compound winding, prevents the capacitive transmission of parasitic signals at that level.

IV. MATERIALS

For this design, the selected magnetic material for the core construction is **Magnesil**, an iron-silicon alloy (Fe 97%, Si 3%). This is after considering many design trade-offs such as maximum power loss; minimum operating efficiency; overall system weight; voltage regulation limits; maximum permissible rise in ambient temperature, optimized size and cost considerations. Table 3.1 gives the basic magnetic properties of the selected core material.

Table 3.1 - Basic Magnetic Properties of Magnesil

Name & Alloy Composites	Initial Permeability (μ_i)	Flux Density B (Tesla)	Curie Temperature (^{0}C)	Coercive Force H_C (Oersteds)	Operating Frequency f (Hz)
Magnesil/Fe 97%, Si 3%	1.5K	1.5-1.8	750 ^{0}C	0.4-0.6	Less than 2 kHz

V. METHODS

This research adopts the use of traditional calculations based on the standard CVT transformer model to accomplish the design and selection of the various system parameters. The following steps were employed to accomplish the design of various parameters.

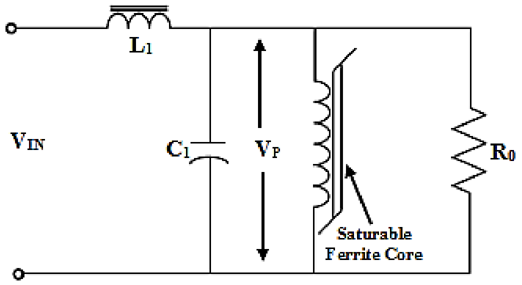


Figure 2. Simple CVT Equivalent Circuit

The operation and power-handling capability of the constant voltage transformer depends on C_1 and L_1 as shown in figure 2 above. Then;

$$LC\omega^2 \quad 1$$

The inductance can be expressed as:

$$L = \frac{R_{0(R)}}{2\omega}, \text{(Henrys)} \qquad 2$$

The capacitance can be expressed as:

$$C = \frac{1}{0.33\omega R_{0(R)}}, \text{(Farads)} \quad 3$$

Assuming a sinusoidal input voltage, an ideal input inductor L_1, and a series capacitor C_l,all voltage and currents are rms values,then V is the voltage value just before the circuit starts to regulate at full load; $R_{O(R)}$, is the reflected resistance back to the primaryat a certain efficiency η, and P_0 is the output power.

$$P_0 = \frac{V_S^2}{R_0}, (watts) \qquad 4$$

$$R_{0(R)} = \frac{(V_P)^2\eta}{P_0}, (ohms) \quad 5$$

To adequately downsize the capacitor values, and allow for increased VA handling capability, additional windings are added on separate cores as this has the effect of reducing the overall ‘stress’ on the cores. Thus the CVT can be modeled as shown in figure 3 below.

The secondary current I_S can be expressed as:

$$\boldsymbol{I_S = \frac{P_0}{V_S}, (amps)} \qquad 6$$

And thus the primary winding current I$_P$ can be related to the secondary current I$_S$ by the expression below:

$$\boldsymbol{I_P = \frac{I_S\left(V_{S(4-5)}\right)}{\eta\left(V_{P(1-2)}\right)}\left(1 + \sqrt{\frac{V_{P(1-2)}}{V_{C(1-3)}}}\right), (amps)} \qquad 7$$

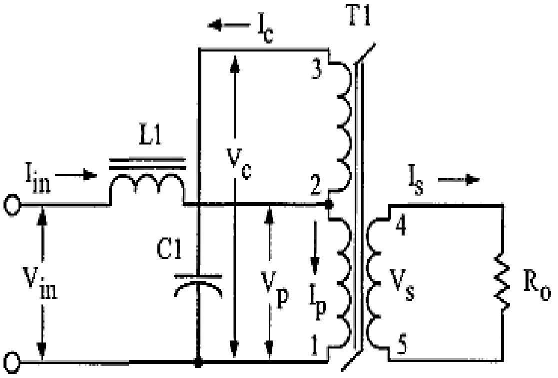


Figure 3. Remodeled CVT Equivalent Circuit Showing Additional Windings

The higher frequency harmonics due to the system ferroresonance cause an increase in the current through the capacitor by a factor K$_C$, and hence the equivalent impedance of the resonating capacitor is reduced to a value lower than its supposed sine wave value. Thus the current through the capacitor I$_C$ is given as:

$$\boldsymbol{I_C = K_C V_C \omega_C, (amps)} \qquad 8$$

Where K$_C$ can vary from 1.0 to 1.5;

And the overall voltage V$_n$ across the specially connected capacitors C$_1$ through C$_4$ with an equivalent capacitance C$_n$ is expressed as:

$$\boldsymbol{C_n V_n^2 = C_{(1-2)} V_{(1-2)}^2}$$

While the apparent power P$_t$ is the combined sum VA of all individual windings:

$$\boldsymbol{P_t = \left(VA_{(1-2)}\right) + \left(VA_{(2-3)}\right) + \left(VA_{(4-5)}\right)} \qquad 9$$

And finally the line voltage regulation of the system is given as:

$$\boldsymbol{\Delta V_P = 4.44 \Delta B_S A_C f N_P (10^4), (volts)} \qquad 10$$

For a given change in line voltage, the output voltage regulation of a constant-voltage transformer is a function of the Square-ness of its B-H loop. Hence for the chosen magnetic material (silicon-steel alloy i.e. 97% Fe, 3% Si), B$_F$ = B$_I$, as illustrated in figure 4 below. The saturation flux density Bs is dependent on the annealing process of the magnetic material. However the annealing process is peculiar to each manufacturer, a factor which impacts on the saturation flux density Bs.

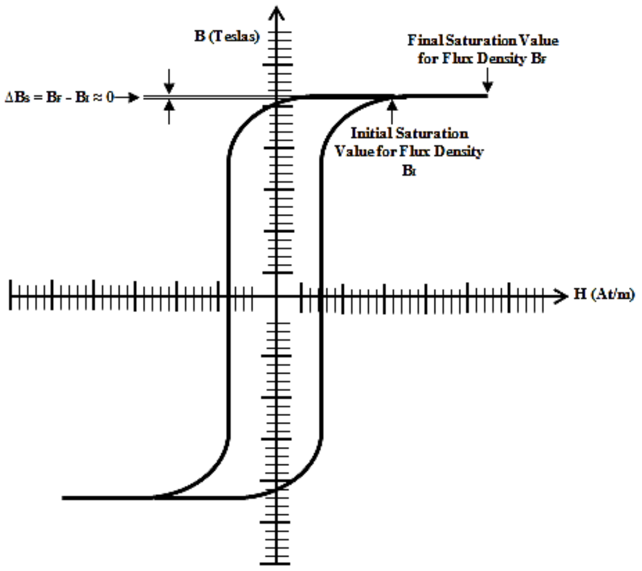


Figure 4. B-H Loop for the CVT Showing Initial and Final Points of Saturation

This research adopts an approach reported by McLyman (2004) in which the area product A$_P$ of a magnetic core is related to its power handling capability by the expression:

$$\boldsymbol{A_P = \frac{P_t(10^4)}{K_f K_u B_m J f}\ (cm^4)} \qquad 11$$

Where:

P$_t$ = Total Apparent Power

K$_f$ = Waveform Coefficient (4.44 for sine wave)

K$_u$ = Window Utilization Factor

B$_m$ = Maximum Saturation Flux Density

J = Current Density

F = Nominal Line Frequency

The number of primary turns for coils a-b and e-f is determined by the expression:

$$\boldsymbol{N_P = \frac{V_P(10^4)}{K_f B_m f A_C}} \qquad 12$$

Where A$_C$ is the core area for each respective winding core.

And the respective primary resistances will be calculated as:

$$\boldsymbol{R_P = (MLT)(N_P)\left[\frac{\mu\Omega}{cm}\right](10)^{-6}\ \text{(ohms)}} \qquad 13$$

Where the mean length turn (MLT) of the core is the figure required to calculate the winding resistance and weight for the core windings.

The primary core loss is calculated as:

$$\boldsymbol{P_{P(CU\ LOSS)} = (I_P)^2 R_P} \qquad 14$$

The number of turns for the required additional windings on the two separate cores T_3 and T_4 is calculated as:

$$N_n = \frac{V_n - V_P}{V_P} \qquad 15$$

The additional winding wire size is calculated as:

$$A_{nW} = \frac{I_n}{J} \qquad 16$$

The additional winding resistance R_n is calculated as:

$$R_n = (MLT)(N_n)\left[\frac{\mu\Omega}{cm}\right](10^{-6}) \qquad 17$$

The additional winding copper loss is calculated as:

$$P_{n(CU\ LOSS)} = (I_n)^2 R_n \qquad 18$$

The secondary winding number of turns is calculated as:

$$N_S = \frac{N_P V_S}{V_P} \qquad 19$$

Secondary winding wire size is calculated as:

$$A_{SW} = \frac{I_S}{J} \qquad 20$$

Secondary winding resistance R_S is calculated as:

$$R_S = (MLT)(N_S)\left[\frac{\mu\Omega}{cm}\right](10^{-6}) \qquad 21$$

Secondary winding copper loss $P_{S(CU\ LOSS)}$ is calculated as

$$P_{S(CU\ LOSS)} = (I_S)^2 R_S \qquad 22$$

Hence the total copper losses $P_{(TOTAL\ CU\ LOSS)}$ is given by:

$$P_{(TOTAL\ CU\ LOSS)} = P_{P(CU\ LOSS)} + P_{n(CU\ LOSS)} + P_{S(CU\ LOSS)} \qquad 23$$

The core loss is given by the expression: $P_{fe} = (W/K)W_{fe}$ 24

Where $W/K = 0.000557^{(1.68)} B_S^{(1.86)}$(watt/kilogram)

The total losses $P_{LOSS(TOTAL)}$ is calculated as:

$$P_{LOSS(TOTAL)} = P_{(TOTAL\ CU\ LOSS)} + P_{fe} \qquad 25$$

Transformer surface watt density ψ is calculated as:

$$\psi = \frac{P_{LOSS(TOTAL)}}{A_t} \qquad 26$$

Where A_t is the total core area.

The expected temperature rise T_r is calculated as:

$$T_r = 450(\psi)^{(0.826)}(°C) \qquad 27$$

Now the actual transformer efficiency η_{real} is given as:

$$\eta_{real} = \frac{P_0}{P_0 + P_{LOSS(TOTAL)}} \qquad 28$$

And finally the window utilization is calculated as:

$$K_U = \frac{N_P A_{Pw} + N_n A_{nw} + N_S A_{Sw}}{W_a} \qquad 29$$

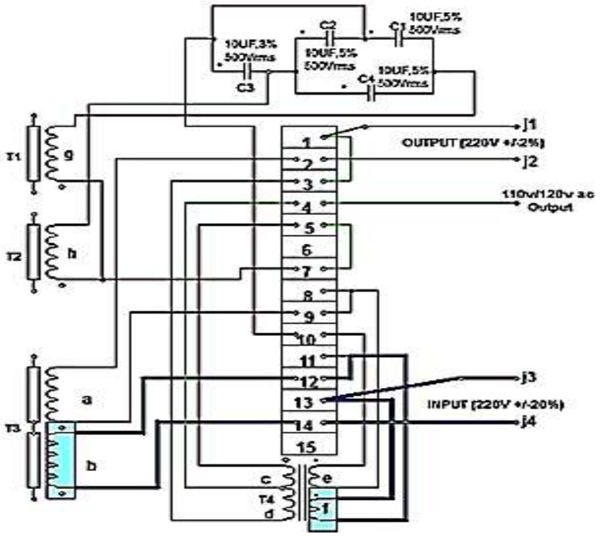
Where W_a is the window area.

Parameter Calculation

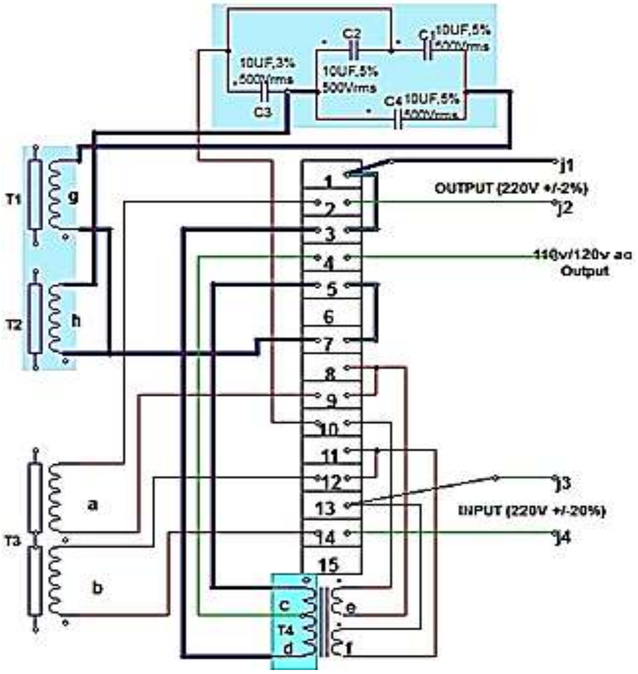
The key design parameters were calculated as follows:	
Required Apparent Power =	10 kVA
Working Power =	8 kW
Minimum Input Voltage =	171 Volts
Power Factor =	0.8
Input Current =	46.78A
Output Current =	36.36A
Output Inductance =	86.54H
Input Inductance =	67.26H
Total Resonating Capacitance =	10μF (500volts)
Saturating Flux Density =	1.15Tesla
Efficiency =	80%
Output Voltage =	220.02Volts

VI. CIRCUIT DESCRIPTION

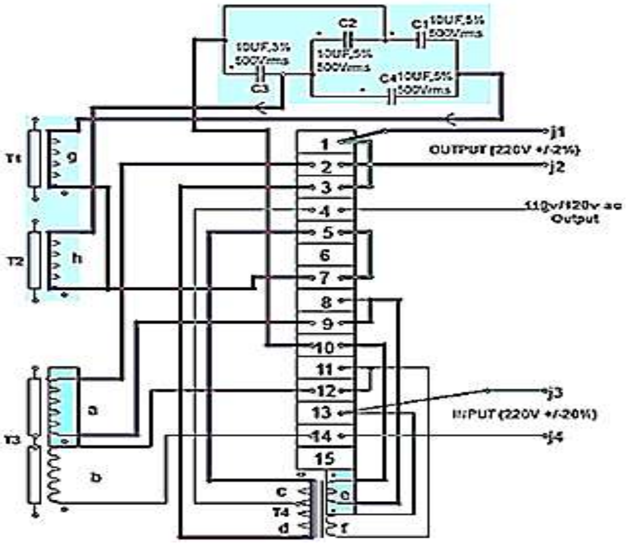
Figure 5 shows the circuit wiring diagram illustrating the various circuit configurations. Coils **f** and **b** form the input section of the CVT; while coils c; d; g; h; e; a**,** and capacitors C_1, C_2, C_3, C_4 form the output section. This design features a transformer with two separate cores; both bearing a part each of primary and secondary windings of the CVT. The result is that a more effective magnetic shunt is created thereby optimizing voltage regulation to near perfection and offering ride-through capabilities during switching or during sag/surge corrections. Thus normal EI laminations are employed that than the special core formations typically used for traditional CVTs. Screwed terminal connections were used to assemble the wiring and component leads together. Various circuits showing primary winding circuit path, the secondary winding circuit path coil c-d interconnecting circuit path with the secondary winding are also illustrated in figure 3.4 (a - c).



(a)



(b)



(c)

Figure 5. The CVT Circuit Configurations: Primary Winding Path (a), Secondary Winding Path (b), and Secondary Winding Path Showing Interconnections with Resonating and Neutralizing Windings

The capacitors C_1- C_4 are connected in a series-series – parallel fashion to achieve filter and compensation. The coils T_1 and T_2 are parallel-connected inductors in effect, which form an auxiliary secondary (neutralizing) winding partly in parallel and partly in series with the capacitors, forming a resonant circuit tuned to attenuate designated harmonics of the mains supply frequency, as well as aid compensation. In other words, the tank circuit serves as a filter to reject harmonics produced by the core saturation and provides the added benefit of storing energy in the form of AC oscillations, which is available for sustaining output winding voltage for up to ½ cycle of input voltage loss.

VII. RESULTS

Figure 6 shows the response of output voltage to variations in input voltages selected in a no-load test carried out using a 300-volt variac, while figure 7 shows the current limiting characteristics. This is an indication of excellent stability under roughly simulated transient conditions (current limiting capability of up to 30% from no-load to full-load).

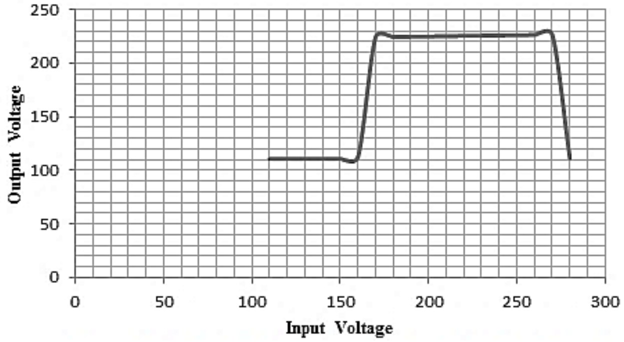


Figure 6. Output Voltage Variation for Selected Input Voltage Values at No-Load

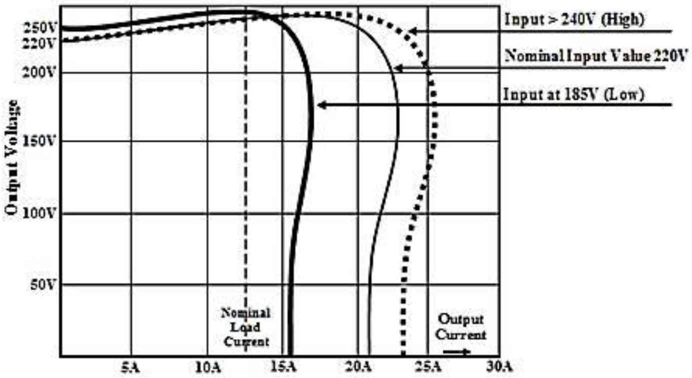
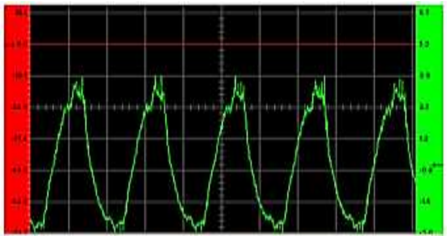
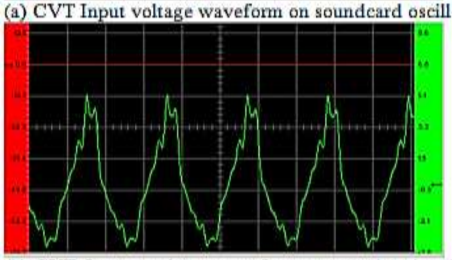


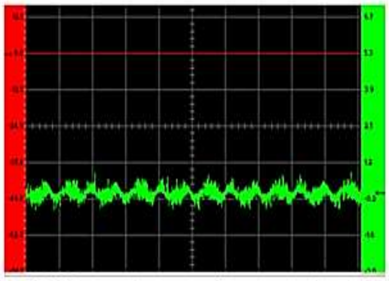
Figure 7. Current Limiting Characteristics for the CVT



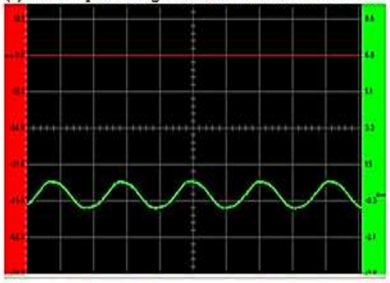
(a) CVT Input voltage waveform on soundcard oscilloscope during starting of motor



(b) CVT Output voltage waveform on soundcard oscilloscope during starting of motor



(c) CVT Input voltage waveform on soundcard oscilloscope during running of motor



(d) CVT Output voltage waveform on soundcard oscilloscope during running of motor

Figure 8. Correction Of Input Distortions in Voltage and Frequency (a-d)

Figure 8 (a to d) shows the results of frequency variation test where a 900W filing machine was connected in series with the CVT input, and that in turn was connected to a 220v ac mains supply. This was to (1) protect the rest of the installation in the workshop (the CVT carries a 10kVA winding transformer), and (2) to introduce low frequency noise to the input and observe the output response on an oscilloscope.

In another test, a 220v 1500w electric heater was connected in series with the supply side of the CVT, again to introduce voltage spike and distortion on the supply. This time, a Storage screen oscilloscope was connected to the input and output of the CVT to view the waveforms. Figures 9 and 10show the output response of the system.

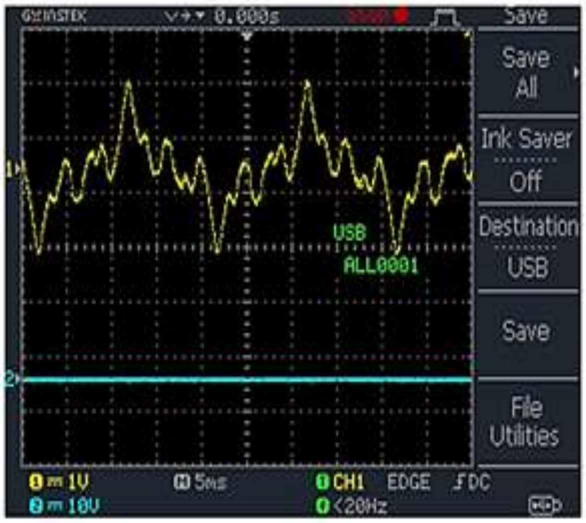


Figure 9. CVT Input Voltage Waveform on Storage Screen Oscilloscope with 1.5 kW Heater Element Connected

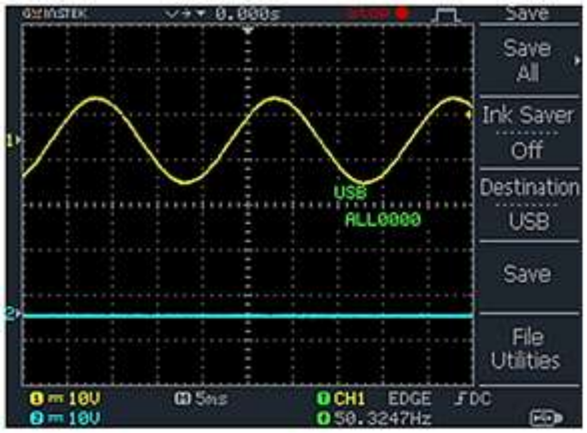


Figure 10. CVT Output Voltage Waveform on Storage Screen Oscilloscope with 1.5 kW Heater Element Connected

Technical Features (Calculated and verified from tests)	
Input Voltage	180 V - 260 V
Output Voltage	220v +/-1%
Line Frequency	50 Hz +/- 0.5%
Efficiency	90% (approx. Under full load)
Output Regulation	2% at No load to full load
Output Wave Form	Sinusoidal
Wave Form Distortion	5% (approx. Under full load)
Power Factor	0.75% lag to 0.9% lead
Ambient Temperature	-5 degree to 50 degree centigrade

VIII. CONCLUSIONS

An optimized design of a 10 kVAconstant voltage transformer is presented. Various design parameters are designed and selected and the construction carried out. The key design objectives were achieved with minor deviations and the expected outputs were realised. This paper introduced an approach in which the primary and secondary windings of the CVT are wound upon two separate saturable cores to create a better and more effective magnetic shunt; as against the traditional method ofusing one core with a flux limiting magnetic shunt. Limitations to the test procedures include inadequate protection for sensitive test equipment, thus tests carried out were limited to screen capture and and scope observation. The research findings provide footprint solutions to the most common Electric Power quality problems at both Utility and Consumer ends. The main features obtained from measured parameters are presented as technical features.

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