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Development and Evaluation of a 2KVA Inverter

A 2KV inverter was designed, developed and tested for household applications. It consists of a heavy duty (24 V, 80 AH), oscillator unit, PWM (Pulse-width modulation) controller unit, driver unit, amplifier unit, center-tap step up transformer and battery charger unit. The battery powered the circuitry and the oscillator section generates the drive signal that is amplified and set up the transformer to produce 240 V supply at the secondary winding connected to the output socket of inverter. The feedback control circuit uses discrete components such as: full wave rectifier, pulse width modulator (IC), diodes and other components to sense the output voltage (or load current). When the feedback senses that the load on the inverter output has increased, the inverter control circuitry acts by increasing the width of the switching pulse in the oscillator section which turn on the MOSFETS. MOSFETS turns on for longer time each cycle, automatically correcting the R.M.S value of the output to compensate for any drop in peak-peak output voltage as well as continuous charging of battery, consequently, maintaining a steady output voltage level in inverter irrespective of the load characteristics. The outputs of the tests carried on the unit shows that that instrument performs satisfactory well.

Keywords: *Inverter, transformer, voltage, control circuit, current, output, MOSFETS, PWM*

1. Introduction

The need for backup power system can never be over emphasized especially in this technological age (Bedford and Hoft, 1977). Everything will use today uses electrical energy, only differing in terms of volume of consumption and sensitivity. Most digitized equipment is considered sensitive because power failure of whatever duration could cause irreversible and undesirable consequences, hence the need for backup system is highly important (Theraja, 2002). It has been discovered that, more than 90% of the countries in the globe cannot boost their power supply at

45% power reliability. This in thus shows that inverters and other auxiliary power sources are very important for perfect power reliability (Daniels, 1982). An inverter is basically a device which converts D.C supply from a battery into A.C power supply required by most electrical equipment appliances and useful as electrical backups available today. Others are the rotating armature generator that uses fuel and the uninterruptible power supply (UPS).

In Nigeria, the standard A.C supply voltage is 240V, in the event of power failure or unavailability of public power supply, the inverter provides 240 A.C from a D.C battery whose voltage and current rating depends on the rating of the inverter and the load connected. The lead acid batteries used in automobiles are very good for inverters; they provide good quality power supply for a long duration and can be recharged once the power is restored. Modern inverters are extremely reliable. Inverters make life simpler and save money for the user, an inverter-battery system provides clean uninterruptible power supply (Gupta, 2005). Generator generates a lot of noise during operation and most of them do not have automatic start-stop in the event of power failure and restoration (Hughes, 1997). In addition, generator has many mechanical parts which require constant maintenance. On the other hand, the inverter works noiselessly, provides completely automatic switching operations, does not produce any harmful emissions and does not require any special maintenance apart from the battery used which requires routing service once in 15-20 days (John, 2000). Some studies have revealed that for a total load of 5KVA or less, the inverter has a comparative advantage over the generator but from above 5KVA the generator has an advantage over the inverter in terms of efficiency and reliability (Lionel, 1998).

They require highly inflammable product such as fuel which emits harmful emission such C0 which is considered to be environmentally harmful and dangerous to human health. Typical applications for an inverter include: Microwave ovens, television, video recorders, computers, and life-support machines in hospitals, air traffic control systems, military installation, power tools and monitoring communications equipment. Having considered the significance and economic importance of stable and uninterrupted power supply to the nation of ours, this research study is therefore aimed to enhance power supply to homes, office, banks and other industrial organizations.

2.1. Materials and methods

Inverter was designed and developed using various sensitive electrical and electronic components such as relay, capacitor, transistor (FET, JFET), Bi-stable multivibrators, monostable multivibrators, transformer e.t.c.

2.1.1. Astable Multivibrator

The astable multivibrator has no stable state for this reason; it is often referred to as oscillator. The diagram of the astable multivibrator is shown in Fig. 1 Below

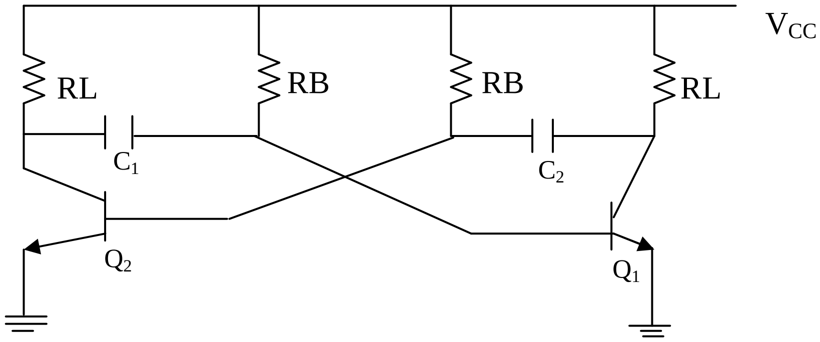

Fig ure 1. Astable Multivibrator

It consists of two similar transistors as the active devices. The transistors are driven either to saturation (ON) or cut- off (OFF). The transistor Q_1 is forward biased by V_{cc} and the biasing resistor R_1 while Q_2 is forward biased by V_{cc} and biasing resistor R_2. The biasing resistors are equal. The collector emitter voltage at Q_1 and Q_2 are determined respectively by load resistor RL_1 and RL_2 together with V_{cc}. The load resistors are equal. When V_{CC} is applied one of the transistors will start conducting before the other does or (slightly faster than the other). It is calibrated characteristics of no two transistors (hfe β V_{be}) are exactly alike. Suppose that Q_1 draws more current than Q_2, this produces a large voltage drop across RL_1, thus creating a fall or (negative) in potential at the collector of Q_1. The fall in potential is transmitted through C_2 to the base of Q_2 where it tends to cut off Q_2 creating a rise in potential at the collector of Q_2 Rise in potential is transmitted through C_1 to the base of Q_1 therefore becomes more forward biased. Decrease in the potential at the collector of Q_1, therefore becomes more forward biased. This series of actions is repeated until the circuit drives Q_1 to saturation (ON state) and completely cutting off Q_2 (OFF state).

Since Q_1 is in saturation, the whole of V_{CC} drops across RL_1 hence $V_{CI} = 0$ and the voltage at the collector of Q_1 is at zero potential since Q_2 is in off (i.e it conducts no current) there is no drop across RL_2. Hence the collector of Q_2 is at V_{cc}. The collector of Q_1 is at OV, C_2 starts to charge through R_2 toward V_{cc}. When the voltage across C_2 raises sufficiently it biases Q_2 in the forward direction so that it starts conducting and V_{C2} decreases. The potential at the collector of Q_2 decreases from V_{cc}. This fall in the potential is applied to the base of Q_1 through C_2; hence the base of Q_1 is reverse biased. This rising voltage at the collector of Q_1 is transmitted. Through C_2 to the biases of Q_2 driving it quickly to saturation and completely cutting off Q_1. Since the collector of Q_2 is at OV, starts charging through R_1 towards the target voltage V_{cc}. When the voltage of C_1 increases sufficiently, Q_1 becomes forwards biased and start conducting. In this way the cycle is repeated. It is seen from the above that the circuit alternates between a state in which Q_1 is ON and Q_2 is OFF and a state in which Q_1 is OFF and Q_2 is ON. The time in each state depends on the CR values. Since each transistor is driven alternatively into saturation and cu-off, the wave form at either collector is essentially a square waveform with peak amplitude equal to V_{cc}.

2.1.2. Transformer

A transformer is a static piece of electrical apparatus by which electric power in one circuit is transformed into electric power in another circuit at the same frequency. It can raise or lower the voltage in circuit with a corresponding decrease or increases in current. The physical basis of a transformer is mutual induction between two circuits linked by a common magnetic flux (Say, 1978). In its simplest form, it consists of two inductive coils which are electrically separated but magnetically linked through a path of low reluctance as shown in plate 1.

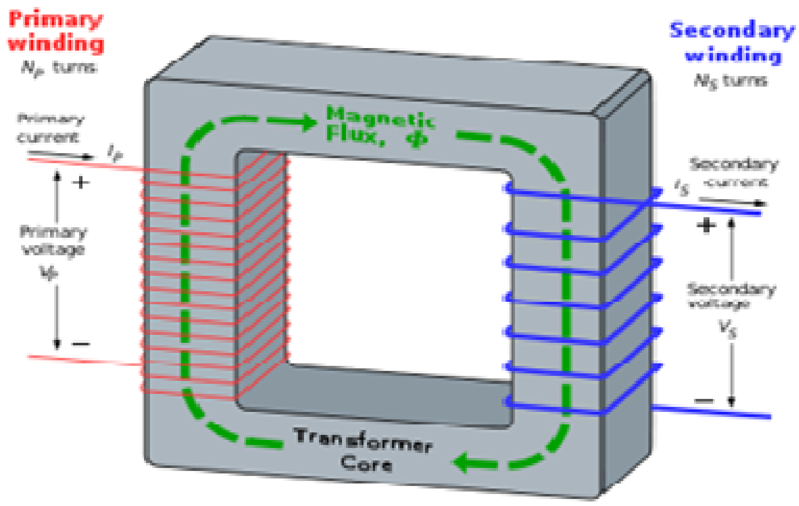

Plate.1: Core type transformer

The two coils possess high inductance. Induced e.m.f is produced.(Faraday's law of electromagnetic induction).

$$e = m \frac{\partial \phi}{\partial T} \qquad (1)$$

Where m = Mutual inductance

Φ = Flux linkage

E_1 is proportional to the number of turns in the primary N_1 and also to the rate at which the flux linking the coil is changing. Thus, there are two important relationships as expressed as follows:

$$V_1 = E_1 \tag{2}$$

$$E_1 = N_1 (\Phi/t) \tag{3}$$

At the same time that flux is changing within the primary coil, it also changes within the secondary coil, since both coils are wound on the same magnetic core.

Since it is exactly the same flux, the rate of changing of flux linking the secondary is identical with the rate of change of flux linking the primary coil. Induced e.m.f (E_2) is proportional to the number of turns in the secondary winding N_2

$$E_2 = N_2 \frac{\phi}{t} \tag{4}$$

$$E_2 = V_2$$

$$E_1/E_2 = N_1/N_2$$

Let: N_1 = No of turns in primary
N_2 = No of turns in secondary

2.1.3. Transformer Design

The specifications and parameters for the design are as follows:

(I) KVA Rating 2000VA
(II) Output Voltage (regulated).....................240V
(III) Input Voltage = 24V............................24V
(IV) Supply frequency = 50HZ......................50HZ
(V) Design Type ....Shell
(VI) Cooling Medium ....Natural Air (NA)
(VII) Number of phase...............................1

(a) Volt per Turn; Et.

When an alternating voltage is applied to the terminals of the windings of a transformer with N number of turns. A current I flows in the windings. The resulting mmf (NI) set up will produce a flux Φ in the core given by:

$$\Phi=\Phi_m \sin wt \tag{5}$$

Where w = 2πf and Φ_m is the maximum value of the flux produced in the core. The flux linkage is given by the expression.

$$\lambda = N\Phi \tag{6}$$

Due to the flux linkage, an e.m.f will be induced in the windings given by;

$$e = \frac{d\lambda}{dt} = \frac{Nd\phi}{dt} \tag{7}$$

$$e = \frac{Nd(\phi_m \sin \omega t)}{dt}$$

$e = N\Phi_m\, \omega \text{Cos}\, \omega t$

$e = 2\pi f N\Phi_m \text{ Cos } 2\pi ft$ (8)

The peak value of this sinusoidal varying emf is given by;

$Ep = 2\pi f N\Phi_m$ (9)

Hence, the expression of the r.m.s value, E is given by;

$$E = \frac{Ep}{\sqrt{2}} = \frac{2\pi fN\phi_m}{\sqrt{2}}$$

Where $\frac{2\pi}{\sqrt{2}} = 4.44$

$E = 4.44fN\Phi_m$ (10)

But E/N = Volts per turn = E_t

$\therefore$ $Et = 4.44f\Phi_m$ (11)

Taking a factor r such that $r = \frac{\phi_m}{IN}$

Then

$IN = \frac{\phi_m}{r}$ (12)

$\Phi_m = \sqrt{\frac{rx10^{-3}}{4.44f}} \quad X \quad \sqrt{KVA}$ (13)

$Et = K \times \sqrt{KVA}$ (14)

K is a factor depending on r.

Single phase shell type transformer, the value of K varies between 1.01 and 1.25, in this design, K is 1.01

Turns per volt $= \frac{1}{Et}$ (15)

(c) Core Design

(i) Cross-sectional area A_i

$\Phi_m = B_m A_i$ (16)

Where B_m = maximum flux density

For a single phase shell type transformer,

$B_m = 1.5T$ (17)

$\Phi_m = 6.441mwb$ (18)

(i) Window Area A_w

The windings must be accommodated in the window area A_w. Insulation and clearance reduce the available area for the actual conductor cross section to K_wA_w

where K_w is the window space factor. K_w may be quite small if the working voltage is high (Theraja, 2005).

For a single phase transformer

$$K_wA_w=a_1N_1+a_2N_2 \quad (19)$$

$$KwAw = \frac{I_1N_1}{J} + \frac{I_2N_2}{J} \quad (20)$$

$$IN = (I_1N_1+I_2N_2) = K_wA_wJ \quad (21)$$

$$KVA = 4.44f\Phi_m\ KwJ \times 10^3$$

$$Aw=\frac{KVA}{4.44xf\phi_m KwJx10^3} \quad (22)$$

Window space factor K_w is expressed as follows:

$$K_w = 0.1 + 0.08 \log_{10} \frac{[KVA]}{0.1} - 0.2\log_{10} KV \quad (23)$$

In most design work, kw is usually taken as a constant value of 0.36. The current density J is a constant and is taken as 3.2A/mm^2 for a shell type transformer. Substituting the value of Φ_m, K_w J into equation 4.19,

$$A_w = 4.44x50, \frac{2}{x\ 6.441x10^{-3} \times 0.3280 \times 3.2x\ 10^{-3}}$$

$$= 1{,}333 \times 10^{-3}m^2 = 1333mm^2$$

(iii) Window Dimensions

Let W_H = Window Height and W_w = Window Width;

But 3 x width of window = Height of window

If width of window is L, then height of window = 3L

$$A_w = 3L^2 \quad (24)$$

$$L = \sqrt{\frac{A_w}{3}} \quad (25)$$

(iv) Stack Height S_H

$$\text{Net core area } A_i = K_s \times A_g \quad (26)$$

Where K_s is the stacking factor, A_g is the gross core area, for a square sectional core area K_s = 0.95

But S_H X Width of central width W_c :4

$$S_H = \frac{A_g}{W_c} \quad (27)$$

(v) Number of Laminations

$$\text{Number of laminations} = \frac{\text{Stack Height}}{\text{Thickness of laminations}} \quad (28)$$

(vi) Approximate Mass of Iron Core

$$\text{Mass} = \text{Density X Volume} \quad (29)$$

But volume of the core is given by

Volume = $2L_m X \frac{(A_i)}{2}$

$$\text{Volume} = L_m \text{ X } A_i \qquad (30)$$

Where L_m is the mean length of the flux represented by the broken line in fig 2(a) above.

$Lm = 2[(W_H + W_L) + (W_w + W_L]$ (31)

$= 2(W_H + W_w + 2W_L)$

$= 2(63 + 21 + 42)$

$= 252mm$

Volume = 252x 4294 = 10.82 x$10^5$$mm^3$ = 1.082 x$10^6$$mm^3$ = 1.082 x $10^3$$m^3$

But density of steel = 7800kg

From equation (29),

1.082 x 10^3 x 7800= 8.439kg≈ 8.4kg

Approximate Mass of Iron Core will be 8kg

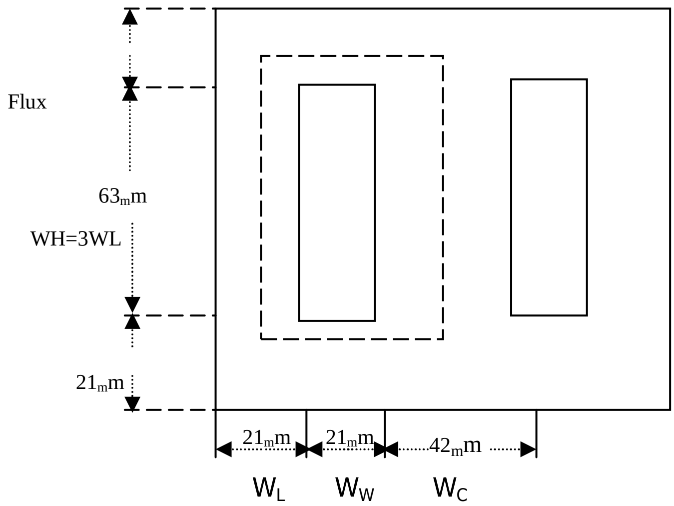

Figure 2. Transformer Core showing path of flux

WH = Window Height, Ww = Window width, WL = Window length

(d) Copper Winding Design

(i) Number of Turns for Primary Windings

Number of turns = Input Voltage x Turns per volt (32)

Number of turns 24 x 0.70 = 16.8 ≈ 17turns

(ii) Number of turns for secondary winding

240 x 0.70 =170 turns

Turn ratio = $\frac{17}{170} = \frac{1}{10}$

(iii) Current rating and diameter of conductor

Maximum current = $\frac{\text{KVA}}{\text{Minimum input voltage}}$ (33)

Transformer losses and efficiency is calculated as follows

Efficiency = $\frac{\text{Power Input} - \text{Losses}}{\text{Power Input}}$ (34)

$= 1 - \frac{\text{Loss}}{\text{Power input}}$ (35)

As shown in the fig.2 below, flux increases from its zero value to maximum value Φm in one quarter of the cycle i.e 1/4f second. Therefore average rate of change of flux is expressed as follows:

$4f\Phi_m$ wb/s (36)

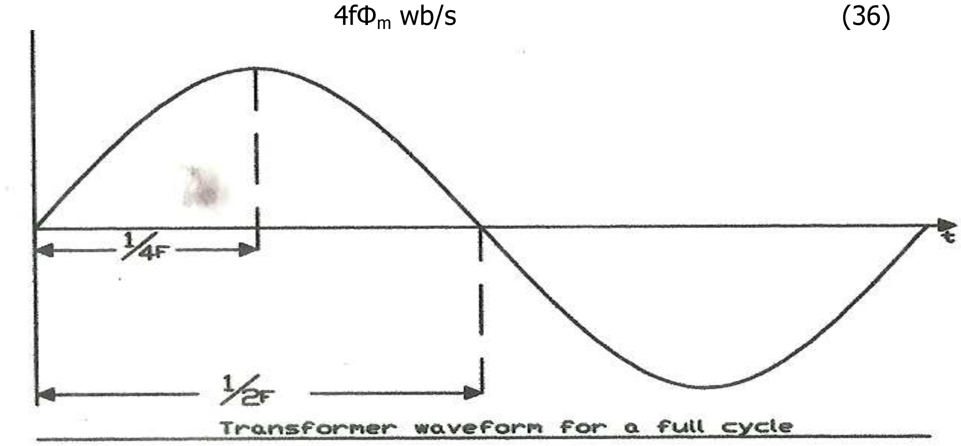

Figure 3. Transformer waveform for a full cycle

Now the rate of change of flux per turn means e.m.f/ turns = 4fΦm volts. If the flux varies sinusoidally, then r.m.s (root mean square) value of the induced e.m.f in the whole primary winding = (induced e.m.f/turn) X No of primary turns.

R.M.S value of e.m.f/turn = 1.11x4fΦm (37)

2.1.4. Opto-Coupler Feedback

The optocoupler used in the design is the 4N35. The chip transfer electrical signals by utilizing light waves to provide coupling with electrical isolation between its input and output, thereby preventing high voltages or rapidly changing voltages on one side of the circuit from damaging components or distorting transmissions on the other side. It contains a source(emitter) of light, almost always a near infrared light-emitting diode(LED),that converts electrical input signal into light, a closed optical channel (also called dielectrical channel) and a photosensor, which detects incoming light and either generates electric energy directly, or modulates electric current flowing from an external power supply. The sensor could be a photoresistor, a photodiode, a phototransistor, a silicon-controlled rectifier (SCR) or a triac. The phototransistor type was use in this research study. The LED has a forward current of 5mA and the photo transistor has a maximum current of 200mA. Conducting current of 1mA, V =220, the limiting resistor is expressed as follows:

$$R = \frac{V_s - V_f}{I_f} \; for V_s = 220, V_f = 2V, I_f = 1mA$$
$$= \frac{220-2}{1X10^{-3}} = 218000\Omega \qquad (38)$$

3.1 Results and Discussion

3.1.1. Transformer testing

The tests carried out on the transformer are;

(i) Open circuit test
(ii) short circuit test
(iii) continuity test
(iv) insulation resistance test

(a) Transformer No – load (Open circuit) test

The transformer was connected as shown in fig 4. The low voltage winding was connected to the supply. The ratio of the voltmeter reading, $^{V1}/_{V2}$ gives the turns ratio of the transformer. Table 1 shows the reading from the experimentation.

Table 1. Open Circuit Test Result

S/N	V_1 (volts)	V_2 (volts)	I_o(amps)	W_{watts}
1	50	5.3	0.092	3.6
2	80	8.5	0.124	7.6
3	110	11.7	0.156	12.0
4	140	15.0	0.195	18.0
5	170	18.1	0.251	27.6

Source: Lab. Experimentation, 2011

I_o = no-load current

(b) Short Circuit Test (Load Test)

As it is observed in Fig 5, the low voltage winding was short circuited through an ammeter A_2 and a low voltage was applied to the high voltage winding. The variac was adjusted to give a voltage that circulated full load currents in the windings. The result is shown in table 2.

Table 2. Short Circuit Test Result

S/N	V	I_{sc}	W_2
1	10	20.2	20
2	20	68.9	80
3	30	98.0	130
4	40	114.0	420

Source: Lab. Experimentation, 2011

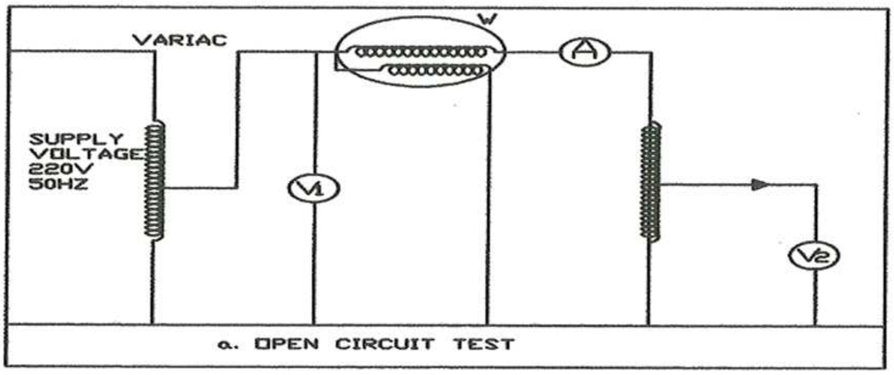

Figure 4. Open Circuit Test

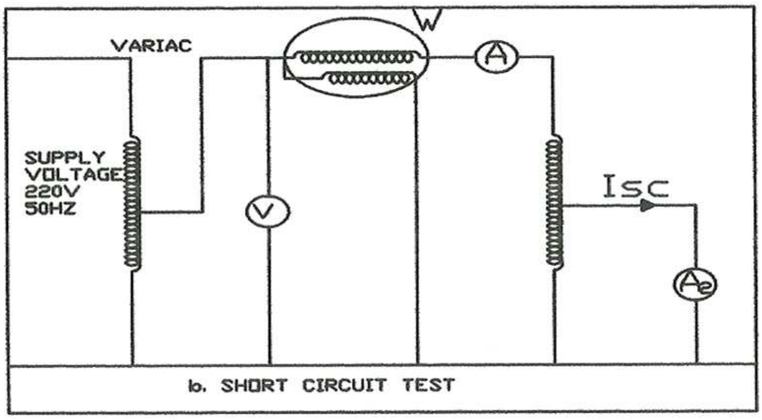

Figure 5. Open Circuit Test

(d) Load test

The result of load test is shown in table 3.

Table 3. Load Test Result Table

S/N	LOAD	OUTPUT VOLTAGE (Volts)	OUTPUT CURRENT (Amp)
1	O Watt (No load)	230	0.047
2	200 Watt Bulb	220	0.56
3	1000 watt electric cooker	210	4.8
4	1TV + 2 FAN + LAPTOP	215	1.5

3.1.2. Determination of the equivalent circuit parameters and efficiency of the transformer from the test results

Open circuit power factor, $$Cos\Phi = \frac{P_0}{V_1 I_0} \qquad (40)$$

Where
P_0 = wattmeter reading on open circuit
V_1 = open circuit primary voltage
I_o = open circuit current (No load current)
From Table 1
$$Cos\Phi_0 = \frac{3.6}{50 \times 0.092} = 0.782$$
$\therefore\ \Phi = Cos^{-1} 0.7826 = 38.49$
$= 38.50$

Core loss component, $I_C = I_0 \ Cos\ \Phi_0$ (41)
$= 0.92 \times 0.782 = 0.071944A$
$= 0.072A$

Magnetizing component; $I_m = I_0 Sin\Phi_0$ (42)
$= 0.092 \times Sin\ 38.50^0$
$= 0.057A$

$$R_0 = \frac{V}{Ic} \qquad (43)$$

$$X_0 = \frac{V_1}{1m} \qquad (44)$$

Where R_0 and X_0 are the branch resistance and reactance respectively.

$$R_0 = \frac{50}{0.072} = 0.694k\Omega \qquad X_0 = \frac{50}{0.057} = 0.877K\Omega$$

The equivalent circuit diagram of the transformer is shown in fig 6. For the purpose of simplicity, the transformer was considered with all parameters referred to the primary winding.

$$Z_{01} = \frac{Vsc}{Isc} = \frac{10}{20.2} = 0.495\Omega \qquad (45)$$

Equivalent resistance referred to primary

$$R_{01} = \frac{W^2}{I^2_{sc}}$$

$$= \frac{20}{20.2^2} \qquad (46)$$

$$= 0.0490\ \Omega$$

Equivalent reactance referred to primary $X0_1 = \sqrt{(Z_{01})^2 - (R_{01})^2}$ (47)

$$X_{01} = \sqrt{0.495^2 - 0.0490^2} = 0.4925\Omega$$

$$\text{Efficiency } \eta = \frac{KVACos\phi}{KVACos\phi + losses} \qquad (48)$$

Where Cos Φ is the load power factor

But total losses = copper loss + iron loss (49)

From table 1: Iron loss = 3.6w = 0.0036kw

Also from table 2: Copper loss = 20w = 0.02kw

Total loss = 0.0036 + 0.02 = 0.0236kw

From equation $\eta = \frac{2.0 \times 0.8}{2.0 \times 0.8 + 0.0236} * 100 = 98.5$ (99%)

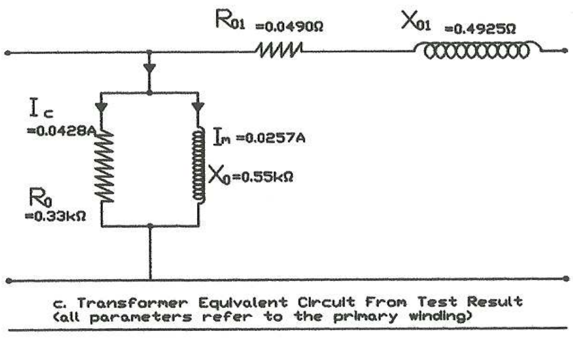

Figure 6. Transformer Equivalent circuit from test result all parameter refer to the primary winding.

4. Conclusion

Alternative power supply source is very important for home and industrial application due to erratic and unrealistic power supply system in Nigeria. This research study is holistically focused on the development of 2KVA which in turns be used for minimization of power surge, reduction in incurred cost for generator fuelling and periodic maintenance. In addition, the inverter is environmentally friendly, easier to operate and optimal functional efficiency could be obtained.

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