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Efficient Power Response Characteristics of 2KVA Low Cost Inverter under Resistive Loads and Inductive Loads

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The paper discussed the design of low cost inverter using SG3525A IC and IRF3205 MOSFET in H-Bridge configuration. The implementation of the real construction involved the use of IC SG3525A for generation of output pulses; the totem pole arrangement of transistors was used in the driver section of the inverter to boost signals as well as switching purposes. The H-bridge configuration was employed to effectively switch the four MOSFETs, this switching produced an alternating potential of 220V. Pre-set conditions such as load condition, low battery cut, overcharge cut and constant output were set at 1700W, 10V, 13.3V and 220V respectively so as to ensure effective and long lasting usage of the inverter. The battery used for the operation of the inverter was 12V maintenance free battery in order to reduce the cost of using the inverter. The various tests carried out on this inverter were tests on inductive loads, resistive loads, home appliances, overload condition, low battery and charging control. The aim of this work is to achieve inverter design analysis under resistive loads and inductive loads for efficient power usage at lowest possible cost. This was achieved by connecting various resistive and inductive loads on the inverter. The results show that the system can operate under both the resistive and inductive loads but operates better under resistive loads, the reason for this is that inductive loads always draw large currents during start-ups which always result to power losses.

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Graphs were plotted and analyzed; the results also showed that this inverter can take up to 1700W of resistive load and inductive load of 1020W. The inverter produced no humming sound from inductive loads and home appliances such as fan, television, refrigerator e.t.c that were within its maximum capacity of 1700W.

Keywords: SG3525; IRF3205; optocoupler; inductive load; capacitive load; MOSFET.

1. INTRODUCTION

It has been man's desire to improve energy; the quest began by creating an avenue for alternative energy source, such as solar energy, nuclear energy, hydro and hydrothermal energy, mechanical energy, fossil fuel among others. The use of all these energies are very expensive, some harmful to the environment, like the fossil fuel. Power generator is needed to burn the fuel in order to generate electricity at desired frequency in an alternating current form. This comes with limitations such as pollution, noise disturbances and also expensive. Nuclear energy requires reactor plant to generate the energy. The maintenance and management of the reactor plant is very expensive and the risk of radiation hazards may be unavoidable [1].

Electricity used for illumination, heating, industrial electric motors, machines, railway tractors etc. has been extended to literarily every sector of the economy particularly for commercial and domestic use. The adequate generation of electric power, stability and efficiency of a power system give great strength to industries, thus, improving the economy of the nation. The standard of living of a nation is improved due to the availability of new jobs for youths. Hence electrical energy generation and efficient delivery will continue to be fundamental importance to the technological advancement of any nation.[2].

More so, the use of additional electric power source such as electric power generators and most recently the use of semiconductor power devices such as the Bipolar Transistor, Thyristors and particularly Metal Oxide Semiconductor Field Effect Transistor (MOSFET) to generate electric power in conjunction with a DC battery in few kilowatts. The role of inverter system in the national energy mix cannot be over emphasized. The global search and the rise in the cost of conventional fossil fuel are making supply demand of electricity product almost impossible especially in some remote areas. Generators which are often used as an alternative to conventional power supply systems are known to be run only during certain hours of the day, and the cost of fueling them is increasingly becoming difficult [3].

Therefore, the increasing use of renewable energy sources (especially solar and wind) has led to a drive in the research and development of appropriate technologies for energy efficient converters. The use of solar photovoltaic generator sometimes requires the inverter. An inverter is a device that takes a DC input and produces an AC output [4]. Simply put, the inverter is a means through which an Alternating Current (AC) is produced from a Direct Current (DC) power of a desired output voltage, current and frequency [5]. The inverter is to be designed to handle the energy requirements of household while yet remaining efficient during periods of low demand. Inverter can be designed in a number of topologies depending on the situation and its requirement. The efficiency of the inverter is highly dependent on the switching device,topology and switching frequency of the inverter [4].

A wide variety of application exist for inverters; this range from stand-alone mode to grid-interactive mode. The mode of operation, capacity (power rating), power quality, among others, determine the technical demand in terms of design input and output for any inverter. With the present focus on sustainable development and environmentally friendly energy sources in the world, the role played by power converting equipment such as inverters is becoming more prominent and for this reason, effort will be needed to draw attention to requirements and standards for their operation [6]. The various applications of the inverter are Wind/solar electrical systems, Back-up for power cells, Generator support systems, Remote homes, Telecommunications, Computers, Tools, Security applications, Mobile power, Boats and yachts, Airplane, Monitoring equipment, Emergency power and lighting etc [7].

The part of its operation to be discussed in this paper, its power response characteristics under inductive loads and resistive loads. This will ensure proper operation and management of the inverter under these loads.

2. METHODOLOGY

2.1 System Design

The inverter comprises of mainly two sections namely: the inverting section (comprising the oscillator, driver and output) and the automation/protection/control section (comprising AC mains sensing, automatic changeover, soft-start charging, charging control, low battery cut, overload protection, shutdown and Pulse Width Modulation (PWM) adjustment). The oscillator used in the inverting section is a 16 pin Integrated Circuit (IC) SG3525A PWM oscillator which is connected in such a way that it compensates for any change in the inverter output by either increasing or decreasing the width of the pulse generated while the driver section is made up of PNP and NPN Bipolar Junction transistors (BJT) with totem pole arrangement and Enhancement-Only N-channel Metal Oxide Semiconductor Field Effect Transistor (E-MOSFET IRF3205) arranged in H-bridge configuration. The output of the inverter is taken from the secondary winding of a transformer connected to the output section of the H-bridge arrangement of four MOSFETs. The low battery cutoff as well as overload protection incorporated into this inverter system was achieved through control IC LM324 which contains 4 voltage comparators, two of which were used for low battery cutoff circuit and two for overload protection circuit. The AC sensing and automatic changeover were achieved by the combination of AC input socket and AC contactor/relay while the soft start or charging delay (9 – 10s) and charging control circuit are being regulated by the control IC LM324. The entire system is an assembly of all these units and other fixtures like switches, cooling fan, sockets, fuse, connectors, AC voltmeter, the casing, battery etc.

2.2 Design Specification

The parameters required to obtain IC's switching frequency are the timing resistors and the timing capacitor which are related to frequency by the frequency formula given in line with SG3525A data sheet and [8] as;

$$f = \frac{1}{C_t(0.7R_t + 3R_D)} \qquad (1)$$

Therefore, to obtain the required frequency;

C_t = timing capacitor with code 104 and the equivalent value is 0.1μF
R_t = timing resistor with value of 100kΩ
R_D = discharge resistor = 0(in pin 7 of SG3525A, there is no discharge resistor)

Then putting these values into equation 1

$$f = \frac{1}{0.1 \times 10^{-6} \times 0.7 \times 100 \times 10^3}$$
$$f = 143Hz$$

The oscillation frequency is 143Hz therefore; the switching frequency will be half of the oscillation frequency which is 72Hz. The variable resistor connected in series with timing resistor will adjust the switching frequency to 50Hz during fine tuning.

In choosing a MOSFET, it is important to consider the peak drive current and power dissipation of the MOSFET due to charging and discharging of the gate capacitance of the MOSFET.

MOSFET driver current rating can be written as [9];

$$dT = \frac{[dV \times c]}{I} \qquad (2)$$

where:

dT = T_{off} + T_{on} (Turn on/Turn off time)
dV = gate voltage
C = gate capacitance gotten from gate total charge
I = peak drive current for a given voltage value
But gate charge Q_g is given as [10];

$$Q = C \times V \qquad (3)$$

Above Equation 2 can be written as;

$$dT = \frac{Q}{I} \qquad (4)$$

Therefore, the peak drive current is given as;

$$I = \frac{Q}{dT} = \frac{Q}{T_{off} + T_{on}} \qquad (5)$$

From IRF3205 data sheet, gate total charge, turn ON/turn OFF delay time are given in equations 3, 4 and 5;

Q_g = 114nC

T_{on} = 14ns
T_{off} = 50ns
dT = 50+14 = 64ns

Therefore, the peak drive current can be calculated as;

$$I = \frac{114nC}{64ns} = 1.8A$$

It will be necessary to connect series of resistance between the MOSFET driver output and the gate of the MOSFET in order to slow the rise of the gate voltage. This is to lower the Electro-magnetic Interference (EMI) noise generated by fast slew rates of MOSFET drain voltage.

Power dissipation due to charging and discharging of the gate capacitance of the MOSFET can also be calculated as [9];

$$\mathrm{P_C} = \mathrm{C_g} \times \mathrm{V_{DD}}^2 \times \mathrm{F} \quad (6)$$

where,

P_C = power dissipation
C_g = gate capacitance
V_{DD} = gate voltage
F = inverter switching frequency
Q_g = 114nC (V_{DS} = 44V)
V_{GS} = 12V

Therefore,

$$\mathrm{Q_g} = \mathrm{C_g} \times \mathrm{V_{GS}} \quad (7)$$

And,

$$\mathrm{C_g} = \frac{\mathrm{Q_g}}{\mathrm{V_{GS}}} \quad (8)$$

Therefore,

$$\mathrm{C_g} = \frac{114\mathrm{nC}}{12\mathrm{V}} = 9.5\mathrm{nF}$$

Using equation 6 above, we have,

$$\mathrm{P_C} = 9.5 \times 10^{-9} \times 12^2 \times 50 = 68.4\mu\mathrm{W}$$

The duty cycle can be calculated using the formula by [11].

$$\mathrm{D} = \frac{\mathrm{t_{on}}}{\mathrm{t_{on}} + \mathrm{t_{off}}} \quad (9)$$

Therefore,

$$\mathrm{D} = \frac{14}{14 + 50} = 0.22$$

The MOSFET has 22% duty cycle.

The output of the inverter is taken from the secondary winding of the transformer and as such, good transformer construction and to specification become necessary. The voltage transformation formula is a very important formula as it gives the relationship between the number of turns in both primary and secondary windings with their corresponding voltages. This is independent of the coil cross sectional area. The formula is given as [8],

$$E = 4.44 f \phi_m N \quad (10)$$

Equation 10 is the EMF equation of the transformer. This equation was used to obtain the area of the core winding, the number of turns both for primary and secondary winding.

For H-bridge topology, we have single primary input of 12V, 220V for the charging terminal and 275V for the inverter output. The flux density used is 1.5T and current density used is 3.5A/m^2
Applying the transformer equation

$$E = 4.4 f B_m N_i A_i \quad (11)$$

Where E = terminal voltage
F = frequency = 50Hz
B_m = maximum flux density = 1.5T
A_i = cross sectional area of the core
N_i = number of turns in the transformer winding
From equation 3

$$\frac{E}{N_i} = 4.44 f B_m A_i \quad (12)$$

Where $\frac{E}{N}$ is volt per turn and is equal to E_t

Therefore

$$\frac{E}{N_i} = E_t = volt/turn \quad (13)$$

Then,

$$E_t = 4.44 f B_m A_i \quad (14)$$

Also,

$$E_t = K\sqrt{PKVA} \qquad (15)$$

K = constant which ranges from 0.8 – 1.2

In this transformer design, K is taken to be 1
P is the output power in KVA.

The core area of a transformer could be achieved through the following:

For the 2KVA design, using equation 15

$$E_t = \sqrt{2} = 1.4\, volt/turn$$

The core area A_i can be calculated from equation 12

$$A_i = \frac{E_t}{4.44fB_m} \qquad (16)$$

Therefore, E_t= 1.4volt/turn, f = 50Hz, B_m = 1.5T

Then we have,

$$A_i = \frac{1.4}{4.44 \times 50 \times 1.5} = \frac{1.4}{333} = 0.0042m^2 = 42cm^2$$

The gross core sectional area A_g can be calculated with the formula given as,

$$A_g = \frac{A_i}{0.9} \qquad (17)$$

Where 0.9 is called the stacking factor which compensates for core or iron losses in the transformer as a result of stacking the lamination together.

Therefore,

$$A_g = \frac{42}{0.9} = 47cm^2$$

This A_g is the actual area of the core used in the 2KVA inverter transformer.

The number of turns for the primary winding is achieved through

$$N_i = \frac{E}{E_t} \qquad (18)$$

For primary winding, the primary voltage E_p is 12V, the number of turns in the primary winding N_p is given as;

$$N_p = \frac{E_p}{E_t} \qquad (19)$$

$$N_p = \frac{12}{1.4} = 9turns$$

The number of turns for the secondary is achieved following this process.

Similarly, the secondary voltage E_s is 220V and the number of turns in the secondary N_s is given as;

$$N_s = \frac{E_s}{E_t} \qquad (20)$$

$$N_s = \frac{220}{1.4} = 157turns$$

For the 275V inverter output

$$N_{s2} = \frac{275}{1.4} = 196turns$$

The out tapping is the difference between the inverting and charging turns, hence,

$$outtapping = N_{s2} - N_s \qquad (21)$$

$$outtapping = 196 - 157 = 39turns$$

The charging delay time can be calculated using the formula given as [8];

$$T_d = 2RC \qquad (22)$$

where,

T_d = delay time
R = resistance = 47KΩ
C = charging capacitor = 100μF
Using equation 22, we have delay time to be,

$$T_d = 2 \times 47 \times 10^3 \times 100 \times 10^{-6} = 9.4s$$

2.3 Working Principle

The source of DC voltage is a 12V free maintenance battery that uses electrolyte paste which is fed into the oscillator SG3525A. Low pulses are generated from the pins 11 and 14 of the oscillator from which the drive signals are taken as shown in Fig. 1, this signals are being amplified by switching transistors in totem pole arrangement shown in Fig. 2 before being fed into the MOSFET inputs arranged in H-bridge configuration as shown in Fig. 3. The high side output of the driver to the MOSFET is connected to diode and bootstrap capacitor in series, this is because to fully turn N-MOSFET on, the voltage to the gate of the MOSFET should be about 10V greater than source voltage and this bootstrap capacitor will help to increase the voltage to the desired value needed by the MOSFET. The switching outputs of the MOSFETs are sent into the primary winding of the transformer which results to an AC voltage of 220V at the secondary side of the transformer. The secondary winding has three terminals; 0V, 220V, 275V. The 220V terminal is for charging the battery when the AC mains supply is available since only one transformer is used in this design in order to reduce the system size. PWM Adjuster is the circuit arrangement used to send a portion of the inverter output voltage connected to bridge rectifier to the error amplifier of the PWM controller in pin 1 of the oscillator in order to be able to keep the final output constant irrespective of loading.

Other functionalities included are low battery and overload protection which shutdown the inverter automatically when the battery voltage falls below reference or the load on the inverter exceeds the maximum set capacity. Also this inverter is incorporated with AC mains sensing circuit and automatic changeover. This section is simply a combination of an AC input socket and an AC contactor/Relay such that once AC main supply is available, the contactor coil is energized, based on the connections at the contacts, oscillator section is cut off (the inverter is shut down), through the relay this AC is sent to the output socket of the inverter, and finally charging is started after some delay set by the soft-start charging circuit. As a result of this, the AC mains sensing circuit leads to automatic changeover. The complete circuit arrangement of the system is shown in Fig. 4.

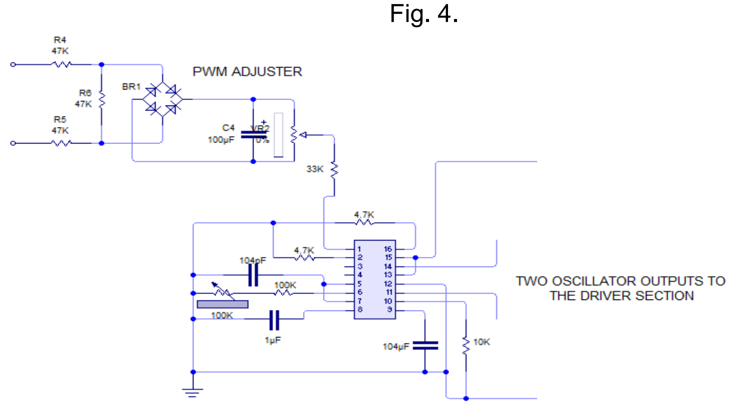

Fig. 1. The circuit diagram of oscillator SG3525A/PWM adjuster

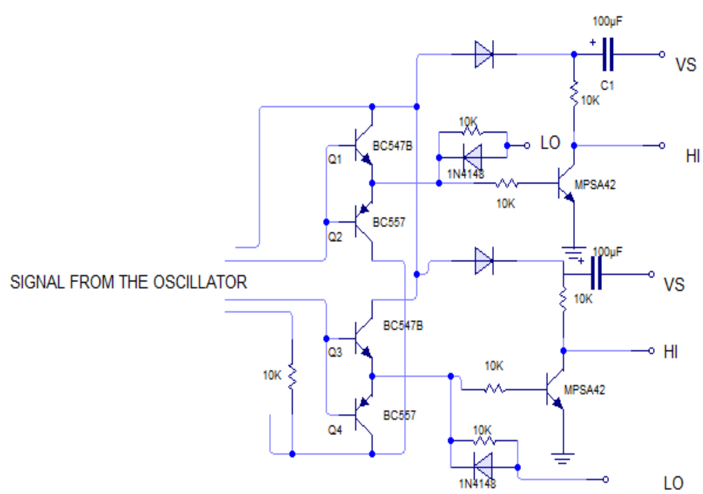

Fig. 2. The circuit diagram of MOSFET driver

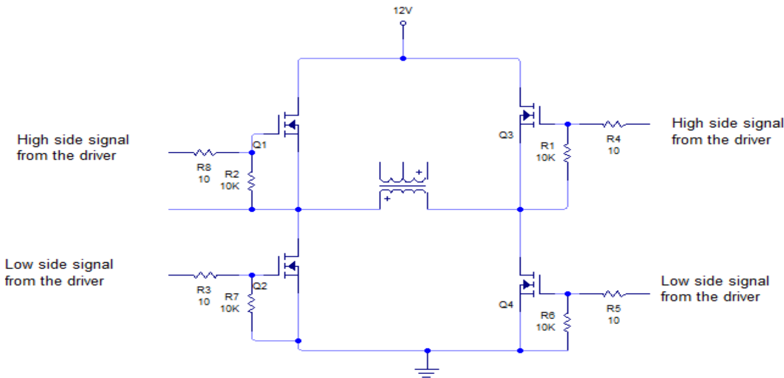

Fig. 3. The circuit arrangement of MOSFET (IRF3205) bank

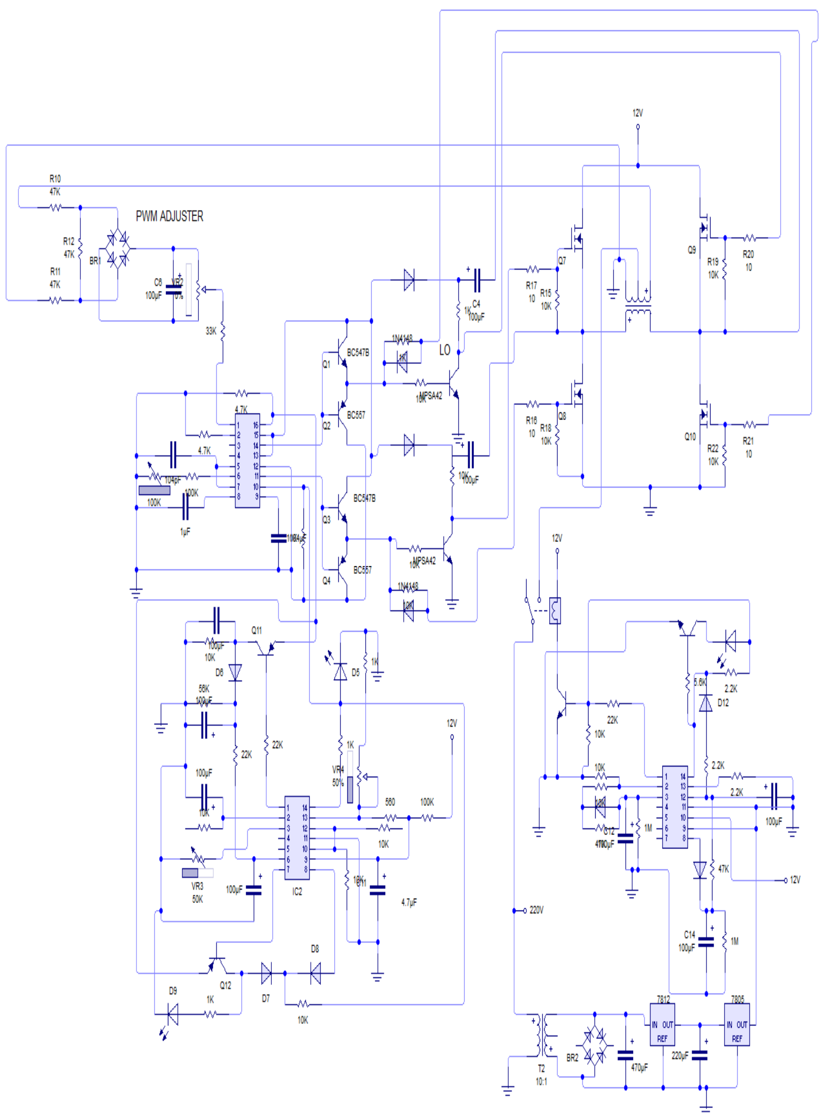

Fig. 4. The complete circuit diagram of a 2kVA power inverter

3. RESULTS AND DISCUSSION

The test on the charging rate of the battery of the system with mains was obtained by taking the voltage of the battery while charging at intervals of 30 minutes.

The 12V battery was discharged to a voltage of 11.8V and the inverter was used to charge the battery, in order to know how efficient the inverter can charge the battery, then test on the charging rate of the battery was conducted by measuring the voltage of the battery at every 30 minutes until at 360 minutes as shown in Table 1. From 300-360 minutes, there are no longer any changes in the voltmeter readings.

The graph of the battery voltage against the time was plotted as shown in Fig. 5 and was observed that battery voltage increased exponentially with time until it gets to its maximum off the battery charger voltage of 13.2V after 300 minutes. The reason why the battery voltage did not increased after 300 minutes was as a result of overcharge battery protector incorporated into the inverter system in order to protect the battery from overcharge.

A graph of power inputs (blue) and power outputs (red) was plotted against various loadings as shown in Fig. 6. From Fig. 6, it can be observed that both the inputs and outputs increase with increase in the various loadings of the inverter, the load conditions are shown in Table 2. When the output power was compared with the input power, it was observed that the input power was greater than the output power, in this way, the efficiencies of the inverter under various resistive loads can be observed. The fractions by which the input powers exceed the output powers increase as the loadings of the inverter increase. The effect of these observations is that the efficiencies of the inverter decrease from smaller loads to bigger ones.

A graph of startup currents (blue) and running currents (red) were plotted against different inductive loads as shown in Fig.7. From Fig. 7, it can be shown that the startup currents of the inductive loads are greater than the running currents, the inductive load conditions are shown in Table 3. The fractions by which the starts up currents exceed the running currents increase as the loadings of the inverter increase. This shows that at start ups, the inductive loads draw more currents than at the normal running of the inductive loads and the currents drawn at start ups increase from smaller loads to larger ones.

The graph of start-up currents and normal running currents was plotted under various inductive loads and is as shown in Fig. 3.

The inverter can hold more resistive loads (up to 1700W) than the inductive loads as it can be seen from Fig. 6 and 7. The reason can also been seen in Fig. 7 where inductive loads start-ups draw large currents and these large currents cause output powers to approach the inverter's maximum capacity under lower load where the system will shut down for overload.

A graph of output voltage against load was plotted as shown in Fig. 8. From the graph, it can be shown that at 300W, the output voltage was slightly above 220V but above 300W, the output adjusted (PWM adjuster) to 220V and this value was maintained irrespective of the increase in load until at 1700W (maximum capacity) as shown in Table 4. Beyond 1700W, the output voltage falls sharply to 0V; this 0V is at 1800W because 1800W is beyond the maximum capacity of the inverter. This happened to protect the inverter from overload.

A graph of voltages at pins 11 and14 (blue) and pin 10 (red) was plotted against loads as shown in Fig. 9. From the graph, it can be observed that from 200W to 1700W, pins 11 and 14 were high while pin 10 was low, at this point, pins 11 and 14 can produce outputs but beyond 1700W pins 11 and 14 fall low and pin 10 goes high, in this condition, no outputs will appear at pins 11 and 14 and this will cause the inverter not to produce output at the secondary winding of the transformer, the pin 10 goes high whenever the load is beyond 1700W (maximum capacity) to protect the inverter from overload. Therefore, for the inverter to produce an output, pins 11 and 14 must remain high and pin 10 low as shown in Table 5.

Since the switching frequency used by electrical appliances in Nigeria is 50Hz, for this inverter to operate effectively under these appliances; the switching frequency of this inverter must be within this frequency value. Therefore, this inverter's switching was observed and measured using oscilloscope and the value obtained was found to be approximately 50Hz. This shows that this inverter frequency is within the frequency specification in Nigeria under which many appliances were designed to operate.

Table 1. Rate of battery charging

Time (S)	0	30	60	90	120	150	180	210	240	270	300	330	360
Battery Voltage(V)	11.8	12.1	12.3	12.5	12.6	12.8	12.9	13.0	13.1	13.2	13.3	13.3	13.3

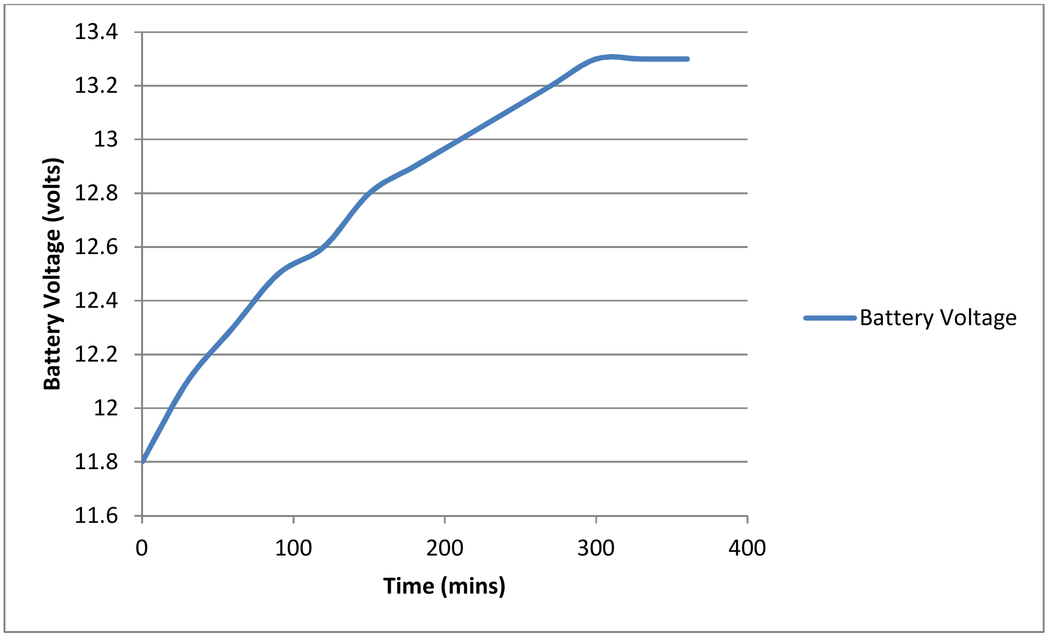

Fig. 5. Graph of rate of battery charging

Table 2. Resistive load readings

	Measured values				Calculated values		
Load (W)	**Voltage output (V)**	**Voltage input (V)**	**Power input (W)**	**Power output (W)**	**Input current (A)**	**Output current (A)**	**Efficiency (%)**
100	220.2	13.2	103.2	94.7	7.82	0.43	91.8
200	220.2	12.9	201.4	184.9	15.61	0.83	91.8
300	220.2	12.8	293.0	268.6	22.89	1.22	91.7
400	220.2	12.7	395.2	363.3	31.12	1.65	91.9
500	220.2	12.6	491.5	442.4	39.01	2.01	90.0
600	220.2	12.5	589.4	541.7	47.15	2.46	91.9
700	220.2	12.5	687.0	618.8	54.96	2.81	90.0
800	220.2	12.4	781.3	709.0	63.01	3.22	90.8
900	220.2	12.3	879.9	799.3	71.54	3.63	90.8
1000	220.2	12.3	979.2	883.0	79.61	4.01	90.2
1100	220.2	12.2	1042.0	935.9	85.41	4.25	89.8
1200	220.2	12.2	1104.5	984.3	90.53	4.47	89.1
1300	220.2	12.2	1178.6	1048.2	96.61	4.76	88.9
1400	220.2	12.1	1275.6	1131.8	105.42	5.14	88.7
1500	220.2	12.1	1345.6	1191.3	111.21	5.41	88.5
1600	220.2	12.0	1396.1	1237.5	116.34	5.62	88.6
1700	220.2	12.0	1454.9	1290.4	121.24	5.86	88.7

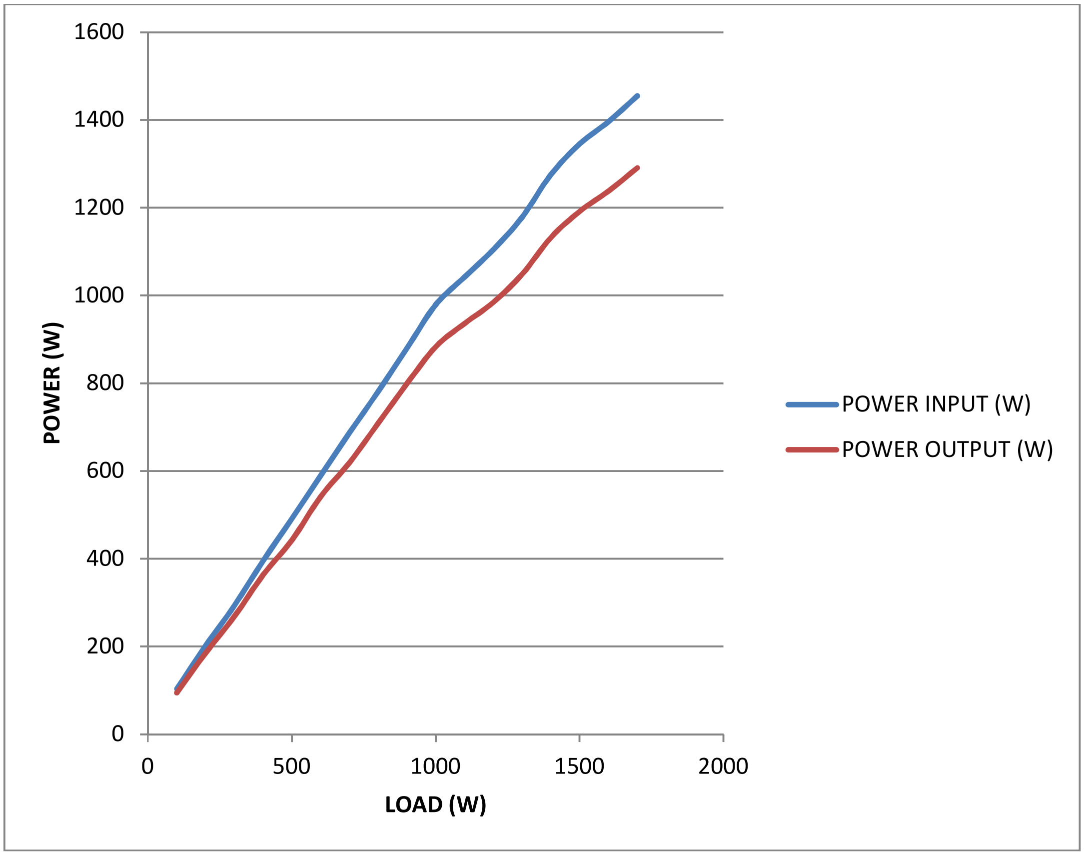

Fig. 6. Graph of resistive load on inverter

Table 3. Inductive load readings

	Measured values					Calculated values			
Load (W)	**Power output (W)**	**Voltage input (V)**	**Power input (W)**	**Start-up power (W)**	**Voltage output (V)**	**Start-up current (A)**	**Input current (A)**	**Running current (A)**	**Efficiency (%)**
60	52.8	13.2	62.4	68.2	220.0	0.31	4.95	0.24	84.6
120	101.2	12.9	121.1	127.6	220.0	0.58	9.61	0.46	83.6
240	204.6	12.8	242.2	253.0	220.0	1.15	19.22	0.93	84.5
300	248.6	12.7	294.1	321.2	220.0	1.46	23.34	1.13	84.5
360	301.4	12.6	355.7	387.2	220.0	1.76	28.23	1.37	84.7
420	343.2	12.5	410.5	459.8	220.0	2.09	32.84	1.56	83.6
480	398.2	12.5	465.5	530.2	220.0	2.41	37.24	1.81	85.5
540	431.2	12.4	512.0	611.6	220.0	2.78	41.29	1.96	84.2
600	481.8	12.3	570.2	695.1	220.0	3.16	45.96	2.19	84.5
660	519.2	12.3	616.1	787.6	220.0	3.58	50.09	2.36	84.3
720	576.4	12.2	679.1	981.3	220.0	4.46	55.21	2.62	84.9
780	618.2	12.2	731.5	1082.4	220.0	4.92	59.96	2.81	84.5
840	657.8	12.2	783.9	1251.9	220.0	5.69	64.25	2.99	83.9
900	699.5	12.1	829.1	1425.6	220.0	6.48	67.96	3.18	84.4
960	728.1	12.1	859.2	1575.3	220.0	7.16	71.01	3.31	84.7
1020	767.8	12.0	907.6	1610.5	220.0	7.72	75.01	3.49	84.6

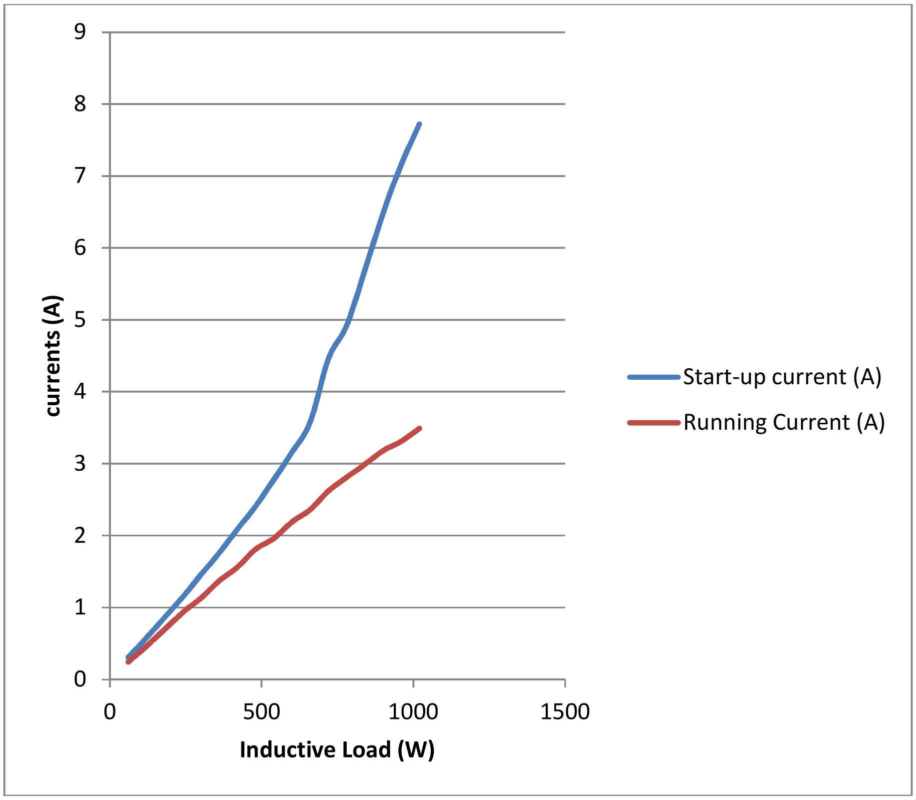

Fig. 7. Graph of effects of inductive load on inverter

Table 4. Readings for overload shutdown

Power (Watts)	Output voltage of inverter (V)
300	222.0
600	220.0
900	220.0
1200	220.0
1500	220.0
1800	0.0

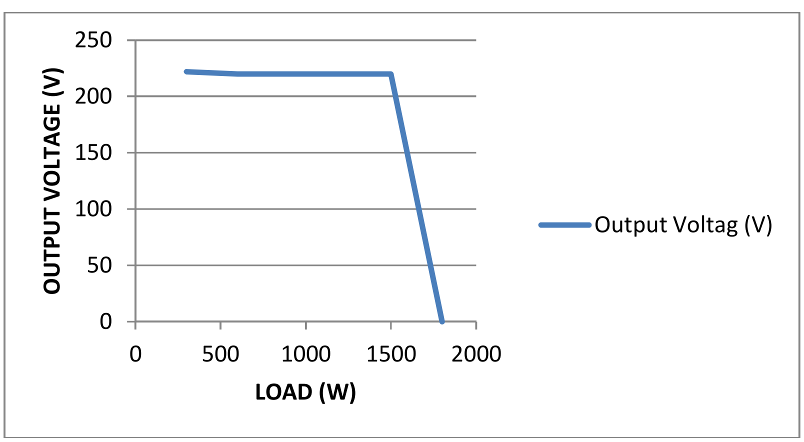

Fig. 8. Graph of overload protection

Table 5. Readings from pins 10, 11 and 14 of SG3525

LOAD (W)	PINS 11 AND 14 VOLTAGE (V)	PIN 10 VOLTAGE (V)
200	4.6	0.0
400	4.6	0.0
600	4.6	0.0
800	4.6	0.0
1000	4.6	0.0
1200	4.6	0.0
1400	4.6	0.0
1600	4.6	0.0
18OO	0.4	5.0

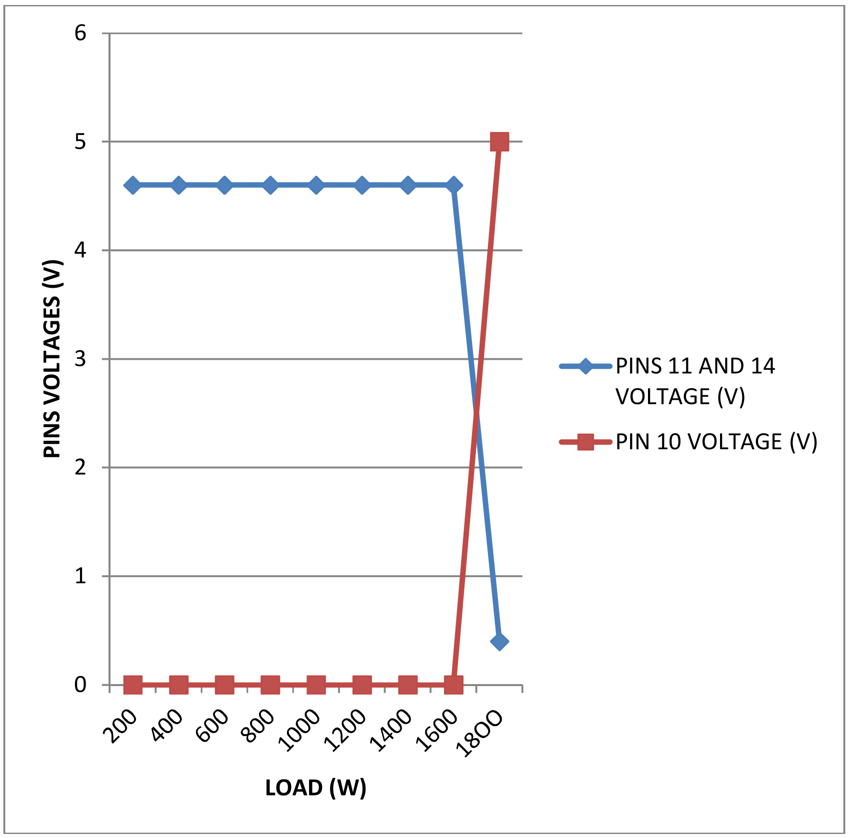

Fig. 9. Graph of oscillator shutdown

4. CONCLUSION

The paper discussed the design of low cost inverter using SG3525A IC and IRF3205 MOSFET in H-Bridge configuration. The aim of this work is to achieve inverter design analysis under resistive loads and inductive loads for efficient power usage at lowest possible cost. This was achieved by connecting various resistive and inductive loads on the inverter. The results show that the system can operate under both the resistive and inductive loads but operates better under resistive loads, the reason for this is shown in Fig. 7, the graph from Fig. 7 shows that inductive loads always draw large currents during start-ups which always result to power losses.

Protective circuitries were also connected to this inverter; such circuitries are overloaded shutdown, low battery shutdown and overcharge cut. These were incorporated to protect the inverter and also to make the system durable. In this inverter, the overload shutdown is at

1700.2W. The required source of DC voltage (battery) was 12V and the resultant output voltage was 220V.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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