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Design and Construction of a 2.5 Kva Photovoltaic Inverter

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Abstract: The epileptic nature of power generation via hydro and thermal sources in Nigeria has given rise to source alternate forms of power generation. The power supply situation is so erratic that some communities are cut off for days, weeks, or months in a bid to ration the low supply from the nation's grid. This gap, period of no supply or cut off from the grid, is what this paper will solve by way of designing and constructing an alternate source using solar power for household use. The design and construction of the unit, a solar powered 2.5KVA inverter was achieved by using a 21/400 turns wound transformer, an SG3524N PMW fixed frequency voltage regulator controller, MOSFET transistors, five80W/18Asolar panel, three200AH deep cycle battery, and a charge controller to monitor the output of the battery for safety. The battery is connected to the inverter circuit to generate 220V alternating current in its output via a step-up transformer. The inverter uses the SG 3524N IC chip fixed frequency Pulse–Width-Modulator (PMW) Voltage regulator controller. The designed oscillation period is set at 50% duty cycle or 0.02 seconds to match the frequency of loads connected to it. From table of results; the inverter was able to maintain stability for 4 hours when a refrigerator and other loads up to a 2000W were connected to it. But at peak sunshine and the solar panel tilted 0^{o} relative to the roof inclination, the inverter output for the same load lasted longer hours.

Keywords: KVA, PWM, SG3524N, MOSFET, Photovoltaic, Power Factor

1. Introduction

Photovoltaic inverters are inverters either used for day system only or for day and night periods [1]. The later describe the ones that have battery backup for use when the sun is down or cloudy. The simplest and least expensive photovoltaic system is the day use and consists of module wired directly to an appliance with no storage device. When sun shines on the modules, the appliance consumes the electricity generated. Higher isolation (sunshine) levels results in increased power output and greater load capacity. Hybrid describes system with battery storage. The battery backs up power to the inverter connected to it during periods of less isolation and at night. The battery is usually charged during sunny period with PV modules or alternate source to keep it ready for use during the night. Another hybrid system approach is a PV system integrated with a wind turbine. Adding a wind turbine make sense in the location where the wind blows when the sun doesn't shine. In this case, consecutive days of cloudy weather are not a problem so long as the wind turbine is spinning [2], [5] and [6].

These forms of inverters are available in the market to drive light loads in the range of 500 to 1000watts. Higher wattages are realizable by calculating a household total electrical load and sizing the entire system (inverter, PV array and battery) to meet such loads. It is this aspect that roused our design and construction interest.

1.1. Sizing the Entire System

Many methods exist for sizing a system output for optimum performance. One method makes use of "solar calculator" where all electrical loads are manually calculated and uploaded to the calculator for sizing. Alternatively, data of energy consumption provided by an electric utility company [like Enugu Electricity Distribution Company (EEDC) electric bill] can be uploaded for sizing.

Manual sizing as used in this design is also possible. This is achieved by use of worksheet to calculate loads for consumption. The format followed is listed below [1]:

- List all of the electrical appliances to be powered by the system.
- Record the operating wattage of each item following the

previous step.

- Specify the numbers of hours per day each item may be used.
- Multiply the first three columns to determine watt hour usage per day.
- Enter the number of days per week that each item will be used to determine the total watt hour per week each item will require.

For equipment ratings, check the label of equipment and record their values accordingly, otherwise check with local appliance dealers or product manufacturers for information.

1.2. Relivance of Project

The major problem solved by this design is regularity of electricity supply at all times, as the battery will be constantly charged during day periods without affecting the integrity of the battery during night periods when it will be used as an alternate source if supply from the national grid fails.

2. Method

Sizing of the PV panel is critical to the overall efficiency of the entire system. The inverter sizing is application-specific and depends on manufacturer guidelines, available inverter sizes in the market and country's climates and regulations (in compliance with grid codes) [8]. The PV inverters are also sized based on the minimum power factor when delivering rated active power of the PV arrays [8]. A calculation that makes use of sizing worksheet was followed with the following load information keyed in for sizing.

2.1. Electrical Load Information

We made use of 2090watts energy consumption for a particular household as average over a six months period. The loads include one washing machine, one TV set, a DVD player, one refrigerator, one blender, bread toaster, electric iron, three fans and thirteen pieces of energy saver lamps, which usage are determined according to time of need.

Table 1. *Load estimation worksheet.*

Individual Loads	**Qty X volts X Amps = Watts X Use X Use ÷ 7 = Watt Hours**									
				AC	DC	Hrs/day	Days/wk	Days	AC	DC
Washing machine	1	220	1.5	330	-	2	3	7	283	-
TV	1	220	0.5	110	-	4	7	7	440	-
DVD player	1	220	0.5	110	-	4	7	7	440	-
Refrigerator	1	220	1.0	220	-	7	7	7	1540	-
Blender	1	220	1.5	330	-	1.5	2	7	47.1	-
Bread toaster	1	220	1.5	330	-	1.5	3	7	70.7	-
Electric iron	1	220	2.5	550	-	1.5	3	7	118	-
Energy saver lamp	13	220	0.5	110	-	0.5	7	7	550	-
AC Total Connected Watts:	2090			AC Average Daily load:			3488			
DC Total Connected Watts: ________________				DC Average Daily Load:________________						

Table 2. *Battery sizing worksheet*

AC Average Daily Load (w-hr/day)	÷	**Inverter efficiency**	+	**DC Average Daily Load (w-hr/day)**	÷	**DC System Voltage**	=	**Average Amp hours/Day**
[(3488	÷	0.9)	+	0]	÷	48	=	80.7
Average Amp-hours/day	X	Days of autonomy	÷	Discharge limit	÷	Battery AH Capacity	=	Batteries in parallel
80.7	X	4	÷	0.5	÷	200	=	3

Table 3. *Array sizing worksheet.*

Average Amp-hrs/day	÷	**Battery efficiency**	÷	**Peak sun Hrs/day**	=	**Array peak Amps**
80.7	÷	0.8	÷	4.1	=	24.6≃25
Array peak amps	÷	Peak Amps/module	=	Modules in parallel		Modules Short Circuit Current
25	÷	5.02	=	4.98≃5		5.4

Table 4. *Controller sizing worksheet.*

Modules Short Circuit Current	**X**	**Modules in parallel**	**X**	**1.25**	**=**	**Array short circuit Amps**	**Controller Array Amps**	**Listed Desired Features**
5.4	X	5	X	1.25	=	33.75	30A	

Table 5. *Inverter Sizing Worksheet.*

AC Total Connected Watts	DC System Voltage	Estimated Surge Watts	Listed Desired Features
2090	12	6270	

2.2. Analysis of Worksheets

Inverter Sizing: From the inverter sizing worksheet, the estimated calculated maximum load was 2090W; the system estimated surge watt which is normally three times of the AC connected loads was calculated to be 6270W. Given these parameters, room was made for sudden addition of load(s); hence a 2.5KVA unit was designed and constructed to meet these needs. The inverter will receive DC power from the battery, and convert it to usable DC and AC outputs. All other subsystems receive information from the output of the power inverter. As such, the inverter is critical to the integrity of the entire system. Safety concerns must be at the forefront of the circuit design [4], [2]. These concerns stem to the safety of the users, as well as the circuitry itself. We recognized this issue, and accounted for it with a properly placed circuit breaker. The circuit was designed so that if a power spike occurred, or something malfunctioned, the key components of the system would be saved, as the breaker opens.

Photovoltaic Array Sizing: The array sizing worksheet provided the number(s) of solar panel(s) to be connected in parallel to fully charge the batteries for optimum use. An approximated number of five 80W/18A panels were calculated to be efficient to consistently charge the battery to capacity and drive the inverter during day time. The solar panel array provided is made by SunForce and is rated at supplying 5.4 Amps maximum short circuit current. Solar panels on their own are not regulated energy harvesters and therefore need regulation circuitry that can also maintain maximum power output [5]. Additionally, the regulation circuitry needs to protect the array from current into itself, which can cause damage to the crystalline silicone structure that converts photons into electrons, hence the need for a controller.

During the research portion of the project,measurements of the solar panelsvoltage and current output with the solar panels loaded with different resistances were recorded. These measurements provided data to graph the panels power curve showing that the panels output a relatively linear current drop from 4.25-3.25A from 1-16V voltage range, then the current drops from 3.25-0.5A from 16-23V. This gave a power curve relationship that was graphed to show where the “knee” point [9] that can determine the maximum power that can be harvested from the solar panel array.

Battery Sizing: Three 200AH Battery was calculated to drive the inverter from the sizing calculations. The average Amp-Hour/Day was calculated to be 80.7AH/day. Given the inverter efficiency of 90% and four days of autonomy, three 200AH deep-cycle batteries in parallel was calculated for the system. Why Deep-Cycle Battery? A deep-cycle battery is designed to discharge between 45% and 75% of its capacity, depending on the manufacturer and the construction of the battery. Although these batteries can be cycled down to 20% charge, the best lifespan versus cost methods is to keep the average cycle at about 45% discharge. There is an indirect correlationbetween the depth of discharge of the battery, and the number of charge and discharge cycles it can perform.

Lead acid batteries are designed to absorb and give up electricity by using a reversible chemical reaction. In battery lingo, a cycle on a battery occurs when you discharge your battery and then charge it back to the same level. How deep a battery is discharged is referred to as Depth of Discharge (DOD). Whereas, in automotive starting, lighting, and ignition batteries (SLI), they have a short or “shallow” depth of discharge, as they are designed to produce a high amount of current in a very short time. *These batteries are not recommended for use in a photovoltaic system, as they would quickly be ruined by the deep cycles required for extended use.* Another advantage isDeep cycle batteries are designed with thicker lead plates, which have less overall surface area than their thinner SLI counterpart. Because of the reduced availability of surface area for chemical reactions, deep cycle batteries produce less current than an SLI type battery, yet they produce that current for longer periods of time. Deep cycle batteries can be discharged up to 80 percent DOD without damage depending on the model. In order to increase battery life, manufacturers recommend discharging deep-cycle batteries only down to 50 percent in order to increase battery life [10]. All of this was taken into consideration and a 30A Solar-Tech charge controller was used to limit the rate at which electric current is added to or drawn from the batteries; and to prevent over charging and protecting the battery from voltage fluctuation, which can reduce the battery performance or lifespan, and may pose a safety risk.

3. Method of Operation

The inverter system is comprised of an Oscillator unit, MOSFET Driver unit, Centre-tap transformer and a Feedback unit. These units are shown in the design and construction circuit diagram of figure 2. The method of operation of each unit is explained thus:

3.1. Oscillator Unit

We used an SG3524 IC to generate the PWM signal, off of which we would create the square wave output. A general overview of the internal circuitry of this IC can be observed in Figure 1 below.

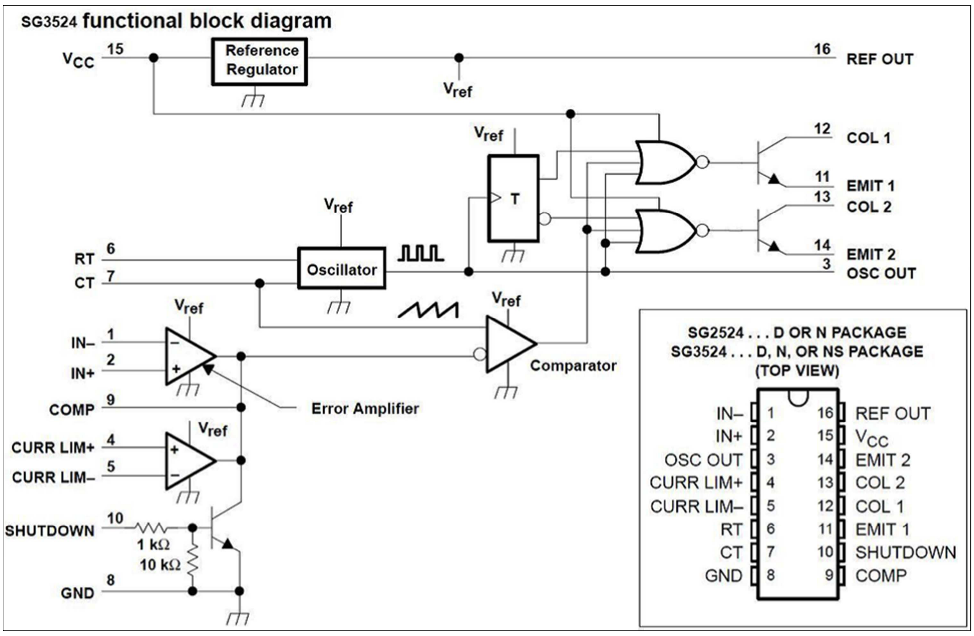

Figure 1. *Pin assignment of the SG3524N IC [11].*

The IC is the heart of the inverter circuit, and was heavily protected by fuses. The circuitry which utilized the SG3524N to create an output signal can be seen in Figure 2. Following the circuitry surrounding the SG3524Nis the MOSFET circuit. The integrated circuit chip SG3524N, is used to provide signal oscillations necessary for the inversion from DC to AC and also provides the necessary control of the entire system. The IC (SG3524N) is a fixed frequency pulse-width-modulator (PWM) voltage regulator control circuit. The regulator operates at a fixed frequency ($50H_z$) which is programmable by timing resistor R_1, R_1^1 (100K adjustable and 200K fixed) and timing capacitor C_1. $R_1 R_1^1$ establishes a constant charging current to C_1. This results in a linear voltage ramp at C_1, which is fed to the comparator to provide linear control of the output pulse duration (width) by the error amplifier. The SG3524N contains an onboard 5V regulator that serves as a reference, as well as supplying power to the SG3524N internal regulator control circuitry [11].

The variable resistor 100K and 200K are for voltage and frequency adjustments. More so, the 100K variable resistor can be varied to reduce or eliminate vibration (noise) in cases where motor loads like fans are connected to the inverter unit. The pulse-width-modulation is used to keep the inverter output constant at 220VAC. To ensure constant output, the SG3524N always receives a feedback output of AC supply generated by the inverter. If the IC does not receive the feedback, the PWM output from pins 11 and 14 will also change; this will result in the fluctuation of the inverter output supply. The IC operates best between 5-40volts DC and at temperatures 0-70°C.

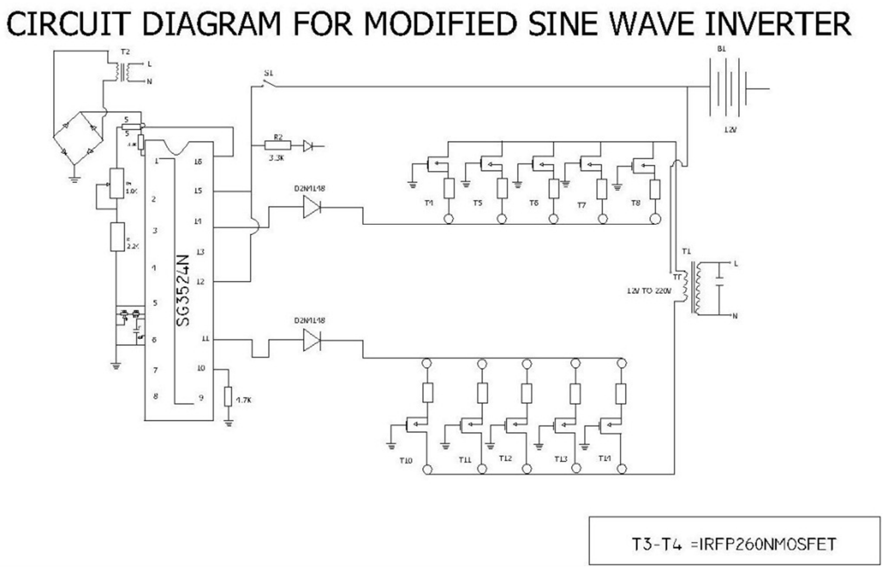

Figure 2. *Complete Circuit Diagram of the 2.5KVA Inverter.*

The frequency of operation of PWM (oscillator) circuit is given by:

$$f = \frac{1.30}{R_t C_t} \quad (1)$$

Where $C_t = 0.1\mu F$ and
F (frequency) is chosen to be 50Hz
R_t = the timing resistor so that,

$$R_t = \frac{1.30}{C_t f} = \frac{1.30}{50 * 0.1 * 10^{-6}} = 260{,}000\Omega$$

$$R_t = 260K\Omega$$

Since 260KΩ cannot be found in the market a 200KΩ fixed and 100KΩ were connected in series to achieve the required resistance. The frequency of operation of the oscillation of the oscillator is determined by the timing resistor and timing capacitor, and fixed at 50Hz, the period (T) of oscillator is given by $T = \frac{1}{f} = \frac{1}{50} = 0.02sec.$ the duty cycle of operation of the oscillator circuits is 50%.

3.2. Mosfet Driver UNIT

The MOSFET used is IRFP26ON. Its configuration values from transistor data book is stated below:

Type: IRFP260N (N-Channel); Device: MOSFET; Short Description: VMOS; Voltage:200V; Current: 46A; Power: 280W; Resistance: <55mΩ (28A) [12].

In the forward direction - that is, supply from the battery to the load - receives the oscillated DC voltage signal, boost the power and conducts in positive and negative half cycles thereby producing an AC output which can then be stepped up by the transformer to the required AC voltage of 220V. On the other hand when used in the reverse direction, this unit can be used to charge the battery from the main supply through the switching circuit (relay) in the control unit, if need be in case of failure from the charge controller. This follows the normal rectification process. Fig. 3 shows the designed MOSFET circuit.

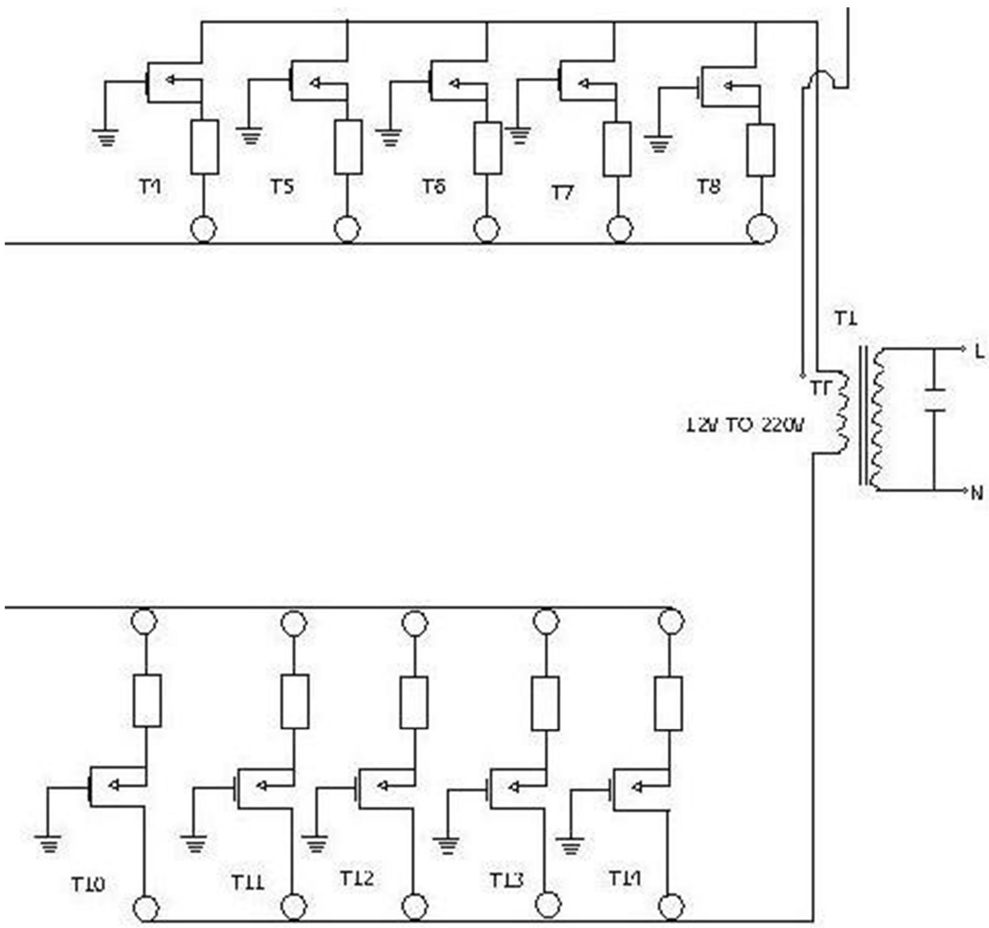

Figure 3. *Designed MOSFET circuit.*

From figure 3 during the positive half cycle of the input AC signal, the first set of MOSFETs conducts acting as diode but in the reverse direction (cathode to anode), a 12v DC voltage is presented at the Centre-tap terminal of the transformer which serves as a positive input to the battery, since the negative terminal of the battery has been connected to the source of the MOSFETs. During the negative half cycle of the input signal, the second sets of the MOSFETs conducts and the same process occurs. What this means is that the oscillator (SG3524N) generates two separate signals from pins 11 and 14 which switches the MOSFETs gates on either sides. The supply from the battery to the load receives the oscillated DC voltage signal; boost the power and conducts in the positive and negative half cycles thereby producing an AC output which is stepped up by the transformer to the required AC voltage of 220V.

3.3. Centre-Tapped Transformer (Step-Up)

The centre-tapped transformer steps-up the voltage from 12 v AC to 220vAC. The designed and constructed transformer is shown below in figure 4.

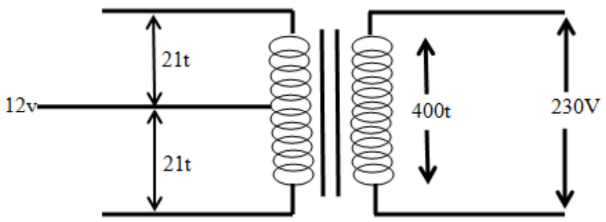

Figure 4. *Designed and wound Step-up Transformer.*

From transformer equation:

$$V_p/V_s = Ns/N_p = K \ldots \quad (2)$$

Since the expected primary and secondary voltages are 12V and 220V, the secondary turn ratio (volts/turn) is given by:

$$N_s = V_s/e_n. \quad (3)$$

$$12/0.574$$

$$= 21\text{turns}$$

V_s and e_n are the secondary voltage and e.m.f per turn respectively.

$$N_s = 220/0.574 = 383.28$$

Which is approximated to 400 turns.

e_n is a table value gotten from the SWG table.

The primary coil is wound with wire gauge 10 and the secondary SWG 18 was used respectively for the above voltages using the calculated turn's ratio. The coil thickness gives a power transformer of 3500W continuous.

3.4. Feed Back Unit

The feedback unit is optional and it is what made this design unique, strong in terms of instantaneous loading, and reliability. It is composed of a transformer T_2, a bridge rectifier and resistor as shown to the left of figure 2. The feedback unit stabilizes the output power in the event of sudden rise in load voltage, as seen when compressors in refrigerators and air conditioner are starting. It acts as a governor to balance the drop or rise in output voltage. It also monitors the output and control or prevents voltage fluctuation keeping the output steady at 220V based on the internal circuitry of the SG3524N fixed variable regulator.

4. Conclusion

The test results show that the solar panels output was stable in voltage and current output, enough to charge the stack of batteries connected to it via a charge controller and readily available for use during power interruptions. The design and construction of the photovoltaic inverter was successfully done. The system was tested and functioned in compliance with the model specification. Component mounting were done correctly while the cost and availability of components were put into consideration. All design procedures were duly observed.

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