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Design and Implementation of A 10kVA 48VDC TO 220VAC Ferrite Transformer Based Intelligent Converter for Renewable Energy Utilization

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Abstract:
Power converters are systems that can convert electric power from one form to another through frequency manipulations using a complex network of frequency oscillators, signal conditioners, semiconductor switches and amplifiers. One common example of a power converter is a DC to AC converter with existing design methods based on converting a DC voltage signal to AC voltage using traditional iron core transformers. These systems are bulky and weighty with inherent high level of losses primarily due to the components used. This research seeks to modify existing 10kVA power converter whose output power signal is a modified sine wave with ferrite transformers and Insulated Gate Bipolar Transistors (IGBTs), to produce a pure output sine wave capable of powering household appliances. The approach is to equip the design with sensors that will make the system more intelligent than the existing converters. The objectives of this research include to produce a cheaper, smaller size, lighter weight, low loss, pure sine wave and voltage regulated power converter that makes the utilization of solar energy more efficient and provides an environmentally friendly alternative source of power supplies for homes and offices.

Keywords: Eddy current loses, Ferrite transformers, Pure sinewaves, Signal conditioners, Switch mode power supply.

INTRODUCTION

Background of Research

A DC to AC converter is a voltage signal inverting system that changes a DC voltage signal into an AC voltage signal. Low voltage DC signal from renewable energy sources such as batteries, photovoltaic cells and fuel cells can be converted to AC voltage signal for both domestic and industrial electricity needs. Converters can be achieved in different ways depending on the technique employed but the most reliable converter systems are those with sinusoidal output voltage waveforms which results from inverting or alternating a DC signal. The conventional AC voltage supply is a pure sine wave, and it is basically being simulated with the help of this conversion technology. Thus, the output of the conversion system is required to be as close as possible to a pure sine wave for effective utility. The basic converter designs involve creating a low frequency time-varying signal with two alternate outputs from a battery and using it in driving a step-up transformer which is wound to produce 220 - 240VAC at the frequency of 50Hz suitable for use.

The method proposed in this research involves the incorporation of ferrite transformers and the Insulated-Gate Bipolar Transistors (IGBTs). Ferrite transformers are those with ferrite core which is a type of magnetic core made of ferrite on which the windings of electric transformers and other wound components such as inductors are formed. It is used for its properties of high magnetic permeability coupled with low electrical conductivity (which helps prevent eddy currents). Because of their comparatively low losses at high frequencies, they are extensively used in the cores of RF transformers and inductors in applications such as Switched-Mode Power (SMP).

Justification

As the world clamors for lower carbon emission and mitigation of climate change, various institutions and government agencies, the oil and gas industry giants etc., are now diversifying into a low carbon regime and investing in renewable energy utilization. There is heavy dependence on power generation from fossil fuel all over the world, while little attention is paid to the potentials of renewable sources like wind, biofuel, solar etc. Most homes and government institutions like ours lack steady power supply, as such, many have resorted to independent power generations schemes using low to high power generating plants and small-scale solar systems. Output power of these generating sets which are square waves in nature, are generally not good enough because of their eddy current losses for household appliances like electric fans, air conditioner systems, refrigerators, etc. Also, inductive loads like electric fans, air conditioning systems, refrigerators etc., do not function effectively due to excessive losses like switching losses in the drive signals and copper and eddy current losses in the transformers that they impose on power converting circuits. These appliances are significantly dominant in our homes and offices, therefore limiting dependence on solar power supply systems. Hence, it has become imperative to carryout research into developing new methods of constructing an intelligent power converter that effectively compensates for the high losses imposed by inductive loads and produces a pure sine wave, like that obtainable from our day-to-day electricity generators.

Statement of Task

The specific objectives of this research are as follows:

1. To design a $48V_{DC}$ to $220V_{AC}$ signal converting circuit with ferrite transformer and IGBTs using computer packages.
2. To design a network of sensors for system protection and signal frequency, voltage and current measurements.
3. To design a microcontroller circuit that utilizes the sensor outputs through feedback for various control algorithms.
4. To simulate the designed circuits with various signal oscillators until a pure sine wave is achieved.

Review of Existing Prototype

In this research, the existing prototype that was modified has the following specifications.

- Input voltage – 12Vdc
- Output voltage – 210Vac
- Output power – 450W
- Output signal waveform – modified sine wave

The results from the tests carried out on the prototype revealed significant power losses as result of the output waveform and quality of ferrite transformer used for the construction. Overall, this research is targeted at improving the capability of the existing prototype to produce a pure sine wave, higher power output that is usable for several electrical appliances and to make intelligent decisions based on specified conditions.

REVIEW OF RELATED LITERATURE

Switched systems such as SMPS are a challenge to design since their models depend on whether a switch is opened or closed. R. D. Middlebrook from Caltech in 1977 published the models for DC-to-DC converters used today. Middlebrook averaged the circuit configurations for each switch state in a technique called state-space averaging. This simplification reduced two systems into one. The new model led to insightful design equations which helped the growth of SMPS. In the early 20th century, vacuum tubes began to be used as switches in inverter circuits (Gurdjian & Maxwell, 2000).

In modern inverter circuits, the DC power is connected to a transformer primary through the center tap of the primary winding. A switch is rapidly switched back and forth to allow current to flow following two alternate paths through one end of the primary winding and then the other. The alternation of the direction of current flow in the primary winding of the transformer produces an alternating current in the secondary winding. The electromechanical version of switching devices includes two stationary contacts and spring support moving contact. The current in the electromagnet is interrupted by the action of the switch so that the switch continually switched rapidly back and forth, this electromagnetic inverter switch called vibrator or buzzer was used in vacuum automobile radios. The latest inverter circuits have transistors, FETs, SCRs and other electronic switches incorporated in them because of their numerous advantages over electromagnetic switches. In more advanced designs based on the basic H-bridge topology two different fundamental control strategies called basic frequency-variable bridge converter and PWM control are employed for better signal conditioning in inverters (Kassakian, 1991).

THEORETICAL BACKGROUND OF POWER CONVERTERS

According to Austin (2010), an inverter performs the opposite operation of rectifier. In his work, he stated that "for inverter to perform this function there must exist the oscillator, MOSFET, Transistor and other electronic component." Hence, a typical power inverting system requires a relatively stable DC power source capable of supplying enough current for the intended power demands of the system. Power inverters exist in the following categories based on their output waveforms.

- Square wave converters
- Modified sine wave converters
- Sine wave converters

According to Barnes (2003), a square wave inverter is a type of inverter that is designed for low sensitive applications such as lighting and heating. They further stated that square wave inverter output can produce humming when connected to audio equipment and is generally not suitable for sensitive electronics.

In considering the limitations of square wave and modified sine wave inverters, pure sine wave inverter remains the best and produces quality power to all electrical equipment connected to it. It equally has lesser distortion as compared to modified sine wave and square wave inverters. The historical evolution of the DC power converter utility systems, the research and development strides recorded are all evidence of the viability of power converters for renewable energy utility. The high frequency inverting system has been designed and developed to produce a nearly perfect sine wave that is essentially the same as utility supply grid power. The prospects of high frequency inverters as a smooth, pure, noiseless, and less cost source of electrical energy supply are explored in this project.

As described in work of Manias (2016), basically a power converter, as the name implies, does not produce its own power but simply converts power from one form into another. A stable DC power source is therefore required for the operation of the converter and the effectiveness of a conversion system lies in its ability to compensate for losses and its final output waveform. A converter can produce a square wave, modified sine wave, pulsed sine wave, pulse width modulated wave (PWM) or pure sine wave depending on its circuitry. Common types of inverters produce square waves. One way to measure the purity of a sine wave is the use of total harmonic distortion (THD).

Square Wave and Modified Sine Wave

Square waveform is one of the simplest waveforms an inverter design can produce and is best suited to low-sensitivity applications such as lighting and heating. Square wave output can produce "humming" when connected to audio equipment and is generally unsuitable for sensitive electronics.

The modified sine wave inverters on the other hand produce output waveforms that is the sum of two square waves of which is phase shifted 90 degrees relative to the other. The result is three level waveforms with equal intervals of zero volts; peak positive volts; zero volts; peak negative volts and then zero volts. This sequence is repeated. The resultant wave very roughly resembles the shape of a sine wave. Most inexpensive consumer power inverters produce a modified sine wave rather than a pure sine wave. Switching states are developed for positive, negative and zero voltages. If the waveform is chosen to have its peak values for half of the cycle time, the peak voltage to rms voltage ratio is the same as for a sine wave. The DC bus voltage may be actively regulated, or the "on" and "off" times can be modified to maintain the same rms value output up to the DC bus voltage to compensate for DC bus voltage variations (Manias, 2016).

As in the work of Shaaban, Thomas & Mostafa (2017), the ratio of on to off time can be adjusted to vary the rms voltage while maintaining a constant frequency with a common technique called PWM. The generated gate pulses are given to each switch in accordance with the developed pattern to obtain the desired output. Harmonic spectrum in the output depends on the width of the pulses and the modulation frequency. According to Manias (2016), it can be shown that the minimum distortion of a three-level waveform is reached when the pulses extend over 130 degrees of the waveform, but the resulting voltage will still have about 30% THD, higher than commercial standards for grid-connected power sources.

Barnes (2003) stated that when operating induction motors, voltage harmonics are usually not of concern; however, harmonic distortion in the current waveform introduces additional heating and can produce pulsating torques. Numerous kinds of electric equipment will operate quite well on modified sine wave power converter devices, especially loads that are resistive in nature such as traditional incandescent light bulbs. Appliances with a SMPS operate almost entirely without problems, but if the item has a mains transformer, this can overheat depending on how marginally it is rated. However, the load may operate less efficiently owing to the harmonics associated with a modified sine wave and produce a humming noise during operation. Most AC motors will run on modified sine wave inverters with an efficiency reduction of about 20% owing to the harmonic content. However, they may be quite noisy.

Pure Sine Wave

A power converter device which produces a multiple step sinusoidal AC waveform is referred to as a sine wave inverter. To distinguish the converters more clearly with outputs of much less distortion than the modified sine wave which are three steps inverter designs, the manufacturers often use the phrase pure sine wave converter. From the findings of Taylor-Moon (2013), almost all consumer grade inverters that are sold as a "pure sine wave inverter" do not produce a smooth sine wave output. However, this is not critical for few electronic devices as they deal with the output quite well.

According to Akinwole (2018), in conditions where power converter devices substitute for a standard source of power, a perfect or pure sine wave output is desirable because many electrical products are engineered to work best with a sine wave AC power source. Sine wave inverters with more than three steps in the wave output are more complex and have significantly higher cost than a modified sine wave, with only three steps, or square wave (one step) types of the same power handling. SMPS devices, such as personal computers or DVD players, function on modified sine wave power.

Taylor-Moon (2013) stated that AC motors directly operated on non-sinusoidal power may produce extra heat, may have different speed-torque characteristics, or may produce more audible noise than when running on sinusoidal power. A more complex converter can use more than two voltages to form a multiple-stepped approximation to a sine wave and the step-up transformer can be a ferrite core transformer. These can further reduce voltage and current harmonics and THD compared to a converter using only alternating positive and negative pulses.

MATERIALS AND METHOD

The research method involves the study of various signal oscillation integrated circuits for the selection of a suitable IC for pure sine wave production, design and construction of ferrite transformers and the method of application of IGBTs for signal switching. The following sequence of activities will be employed:

1. The design and development of a power converter circuitry using new design techniques with PIC16F877A integrated circuits, ferrite transformer and IGBTs.
2. Simulation of the designed circuit to produce a pure sine wave.
3. Construction/implementation of the simulated circuit.
4. Testing/results analysis with computer packages; and
5. Fabrication of photovoltaic panel as input to the batteries.

The materials used in this design include 48V ferrite transformer, Irfp4110 MOSFETs, 22N60 IGBTs, Fr5408 fast recovery diodes, 450uf/400V polarized capacitors, PIC16F877A microcontroller, resistors, s8050 and s8550 BJTs, 12V/40A Relays, 7805 and 7812 fixed voltage regulators, etc.

The above components are wired to form the different units of the system.

The units of the system are shown in the block diagram below.

Block Diagram

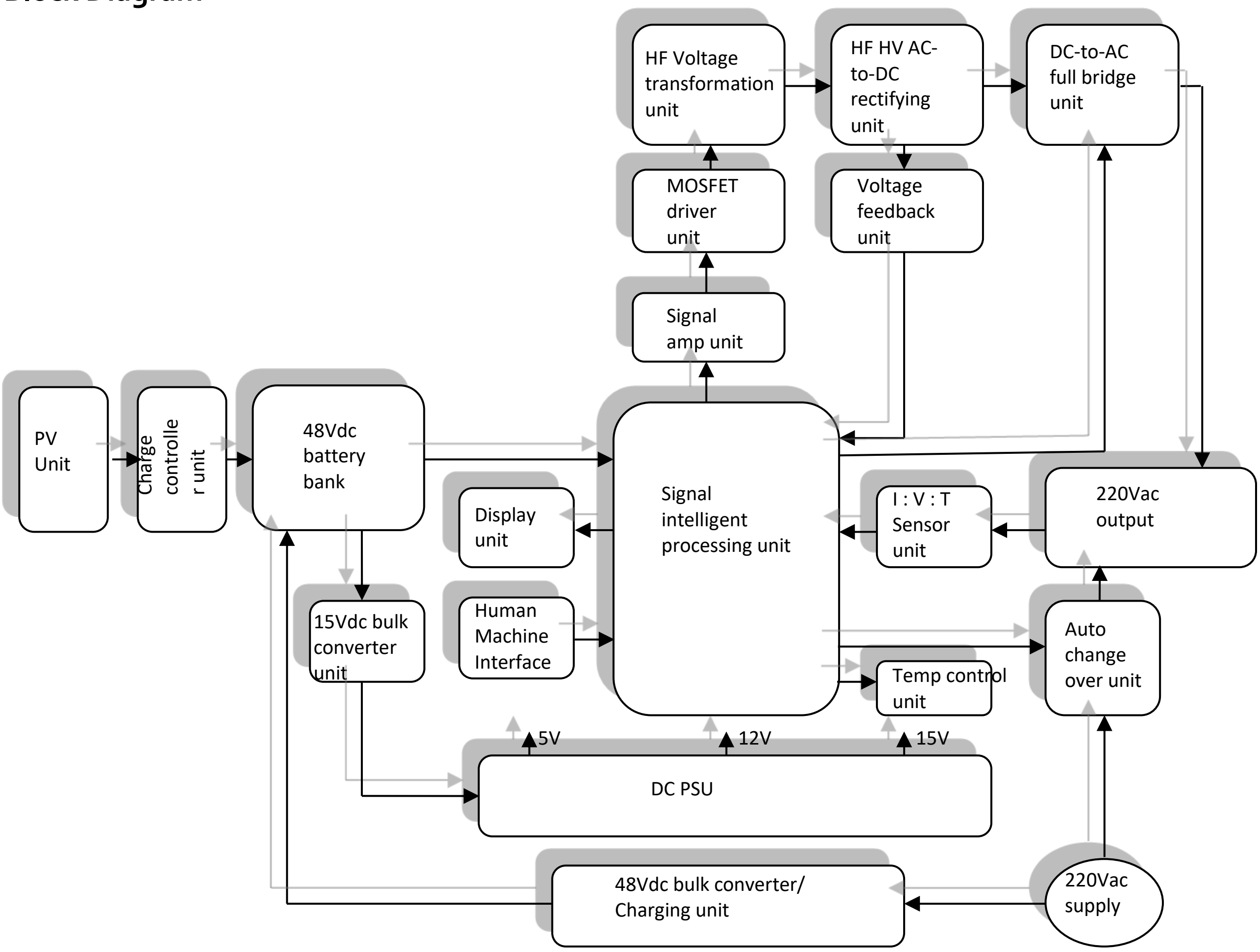


Figure 1 Block Diagram.

Circuit Diagram

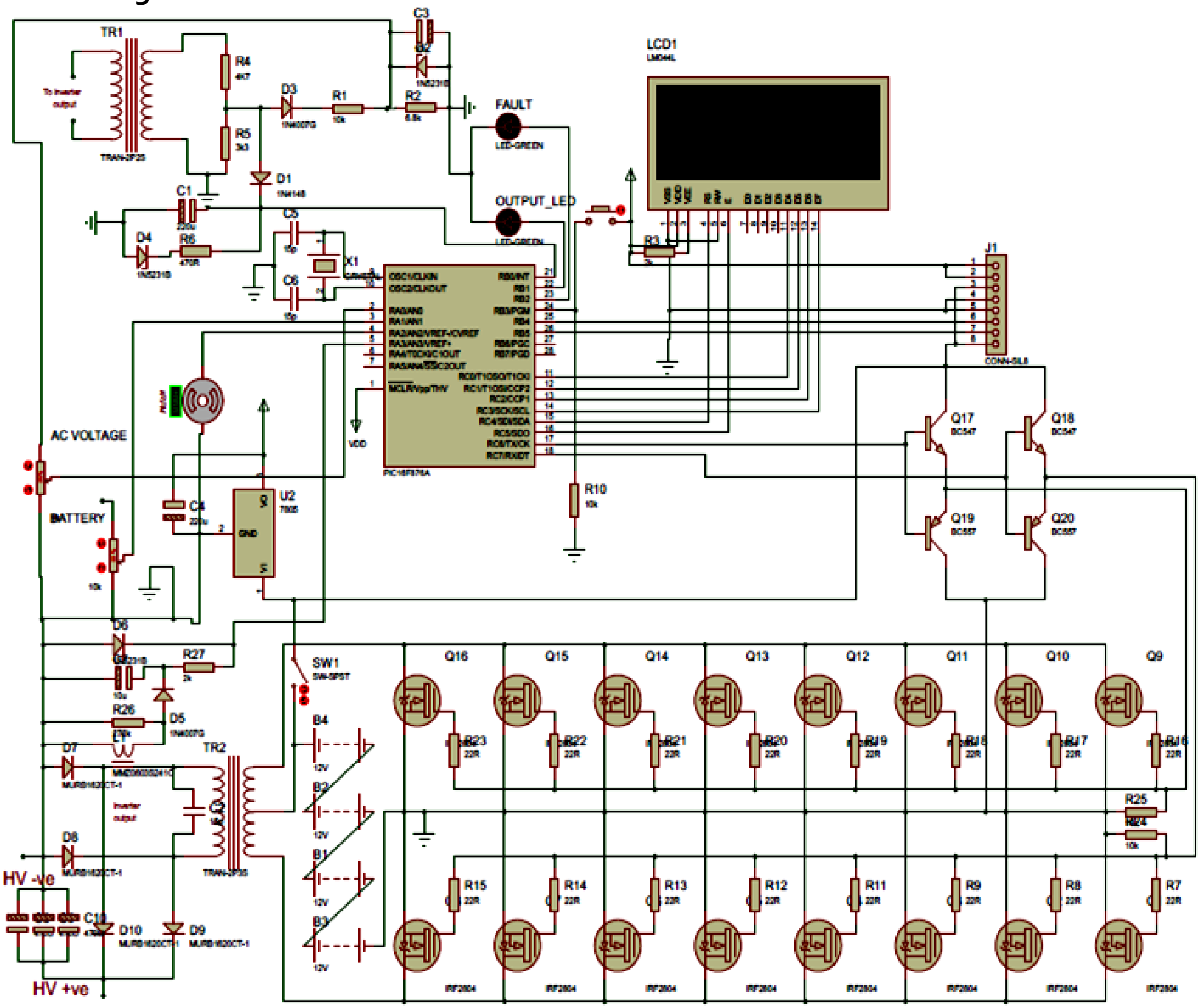


Figure 2: Block Diagram

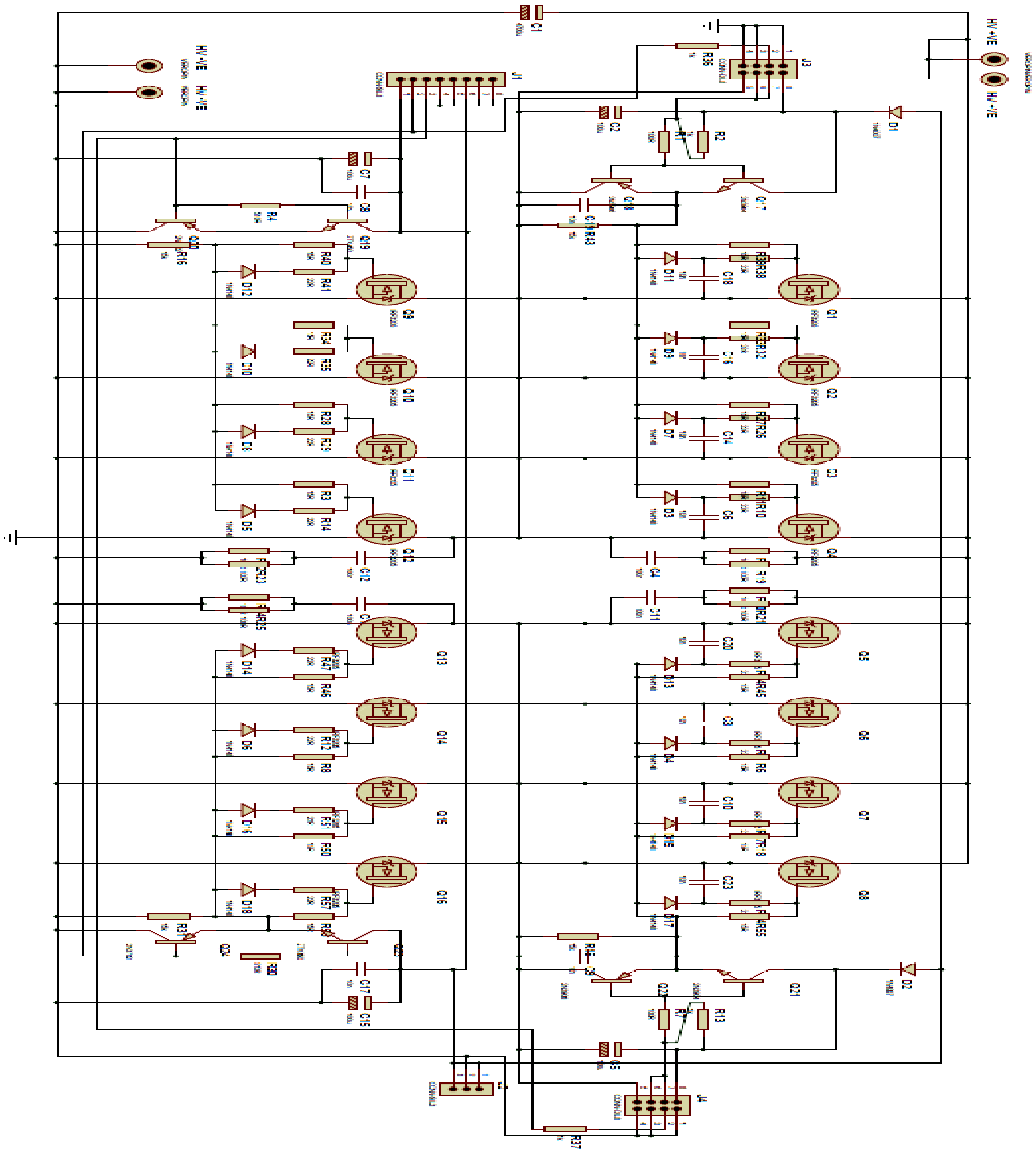


Figure 3: Circuit Diagram.

Design

There are many factors considered in the ferrite power transformer design.

Ferrite is an ideal core material for transformers, inverters, and inductors in the frequency range 20 kHz to 3 MHz, due to the combination of low core cost and low core losses. Ferrites may be used in the saturating mode for low power, low frequency operation (<50 watts and 10 kHz). Ferrite cores may also be used in flyback transformer designs, which offer low core cost, low circuit cost and high voltage capability. Powder cores (MPP, High Flux, Edge®, Kool $M\mu$, MAX, Kool $M\mu$ Hf, and $XFlux$ offer soft saturation, higher $B_{\max}$, and superior temperature stability and are often the best choice for minimum size and robust performance in power choke, inductor, and flyback applications.

EC, ETD AND EER CORES

These shapes combine the benefits of E cores and pot cores. Like E cores, they have a wide opening on each side. This provides ample space for the large wires used for low output voltage switched mode power supplies. It also increases the flow of air which keeps the assembly cooler. The center leg is round, like that of the pot core.

One of the advantages of the round center leg is that the winding has a shorter path length around it (11% shorter) than the wire around a square center leg with an equal area. This reduces the losses of the windings by 11% and enables the core to handle a higher output power. The round center leg eliminates the sharp bend in the wire that occurs with winding on a square center leg. The power handling capacity play significant role in the choice of the ferrite type and shape. Also taking into consideration to keep low the E-field and the kickback voltage, the primary and secondary sides of the ferrite transformer connection in fig 3.1 is adopted.

Core Material: Power magnetics *R*, *P*, *F*, *T* and *L* materials provide superior saturation, high temperature performance, low losses, and product consistency.

T material is used in this design for consistent performance over a wide temperature range and its applications which include Automotive, Electronic Lighting, Outdoor LCD Screens, Mobile Handheld Devices and AC adapters and chargers.

CORE SELECTION BY POWER HANDLING CAPACITY

The Power Chart characterizes the power handling capacity of each ferrite core based upon the frequency of operation, the circuit topology, the flux level selected, and the amount of power required by the circuit. If these four specifics are known, the core can be selected from the Power Chart on page 68.

Core Selection By $W_a A_c$ Product

The power handling capacity of a transformer core can also be determined by its $W_a A_c$ product, where W_a is the available core window area, and *Ac* is the effective core cross-sectional area. Using the equation shown below, calculate the $W_a A_c$ product and then use the Area Product Distribution ($W_a A_c$ Chart to select the appropriate core. $W_a A_c$ = Product of window area and core area (cm4)

- Po = Power Out (watts)
- D_{cma} = Current Density ($cir.$ mils/amp) Current density can be selected depending upon the amount of heat rise allowed. 750 $cir.$ mils/amp is conservative; 500 $cir.$ mils are aggressive.
- $B_{\max}$ = Flux Density (gauss) selected based upon frequency of operation. Above 20kHz, core losses increase. To operate ferrite cores at higher frequencies, it is necessary to operate the core flux levels lower than ± 2 kG. The Flux Density vs. Frequency chart shows the reduction in flux levels required to maintain 100 mW / cm^3 core losses at various frequencies, with a maximum temperature rise of 25°C for a typical power material, Magnetics P material.
- Ac = Core area in cm2 V = Voltage
- f = frequency (hertz) lp = Primary current
- Kt = Topology constant Is = Secondary current (for a space factor of 0.4)

- Np = Number of turns on the primary
- NS = Number of turns on the secondary

Topology Constants K_t

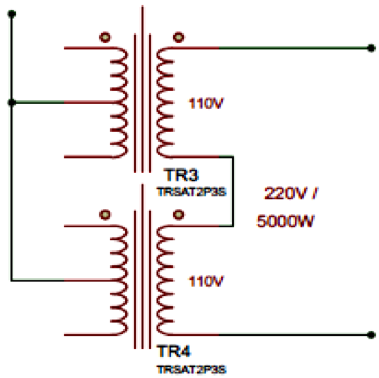
Forward converter = 0.0005	Push-Pull = 0.001(adopted)
Half-bridge = 0.0014	Full bridge = 0.0014
Flyback = 0.00033 (single winding)	Flyback = 0.00025 (multiple winding)

For individual cores, $W_a A_c$ is listed in this catalog under "Magnetic Data."

The $W_a A_c$ formula was obtained from derivations in Chapter 7 of A. I. Pressman's book, "Switching Power Supply Design. Choice of $B_{\max}$ at various frequencies, D_{cma} and alternative transformer temperature rise calculations were gotten from the data book.

$$W_a A_c = \frac{Po * Dcma}{Kt * Bmax * F}$$

For individual core values, $W_a A_c$ can be found in the manufacturer's date book.



From the above circuit, one transformer will be 48V/110Vat 5000W.

Therefore, obtaining data corresponding of the size for the core design above from the standard chart as shown in Appendix xx, the formula applies in evaluating the primary turns of the transformer

$$N_p = \frac{V_p \times 1\grave{0}^3}{48 A_{cf}}$$

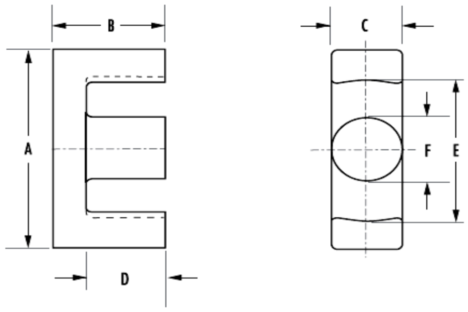
Np = 60 *10^{e8}/ (4*1800*31.6*60000) = 9.6T.

Approximately 10T per 48V at the primary of the transformer and 20T for the complete push-pull circuit.

$$N_s = \frac{V_s \times}{V_p} N_p$$

On the secondary turns, Ns = (120*10)/48 = 25T

Ferrite Core Size:



A=48mm; B =18mm; C=17.6mm; D=11.45mm; E=36.8mm; F=17.6mm

$$N_p = \frac{V_p \times 10^3}{48A_{cf}} \quad ; N_s = \frac{V_s \times}{V_p} N_p \ ; \ I_p = \frac{P_{in}}{V_{in}} , \ I_s = \frac{P_{out}}{V_{out}}$$

Transformer Design

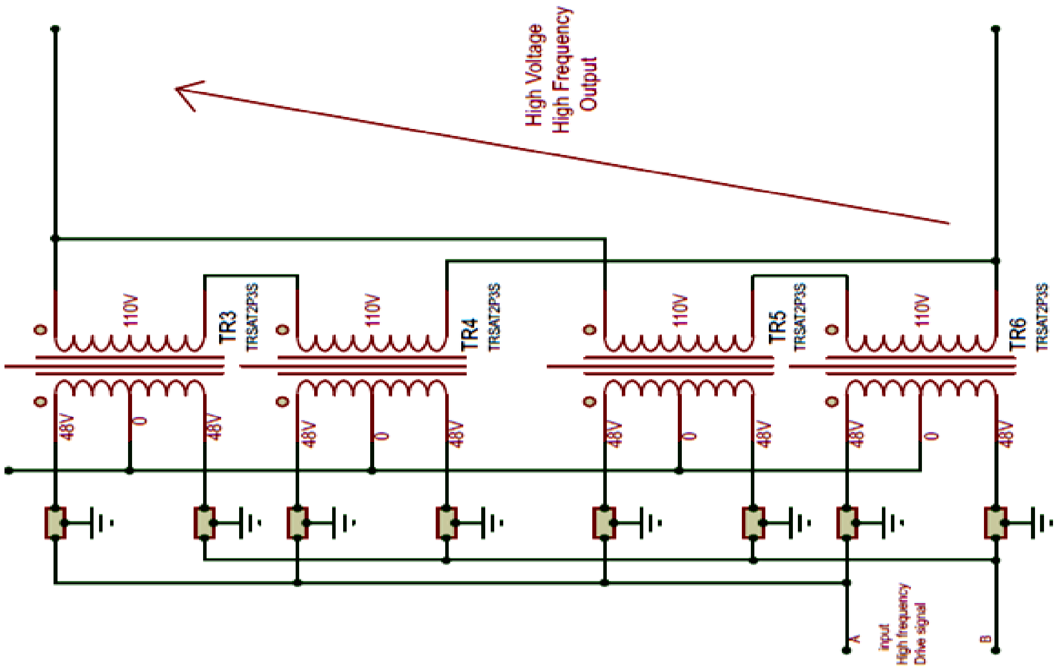


Figure 3: Transformer Design Diagram

Once a core is chosen, the calculation of primary and secondary turns and wire size is readily accomplished.

$$KW_a = N_p A_{wp} + N_s A_{ws}$$

Where:

- A_{wp} = primary wire area Aws = secondary wire area
- Assume K = 0.6 for E-U-I cores
- Assume $N_p A_{wp}$ = 1.1 $N_s A_{ws}$ to allow for losses and feedback winding

$$efficiencye = \frac{P_{out}}{V_{out}} = \frac{P_{out}}{P_{out} + wireloses + coreloss}$$

$$Voltage\,\mathrm{Re}ulation(\%) = \frac{V_{noload} - V_{fulllooa}}{V_{fullload}} \times 100$$

Principle of Operation

The entire physical design of the intelligent converter is built around a microcontroller PIC16f877A. The microcontroller, which is the key component in the design, forms the signal processing unit of the system. According to the instruction written (in language) and programmed to the ROM of the microcontroller, the controller generates signals suitable for the High-Frequency (60KHz) ferrite driving circuit and for the full-bridge inverting circuit. The PIC microcontroller in the signal processing unit also receives signals from the current transformer, LM35 temperature sensor and the potential divider circuit used in calibrating the 48V battery voltage and the 220Vac output voltage in the system. The signals received are processed, tested against the acceptable safe values based on the programmed instructions embedded in the microcontroller. The system therefore converts 48Vdc power from the Battery bank at high frequency 305Vdc and then to 220Vac|50Hz before the monitored power is switched to the load. The logical implementation code for the intelligent converter using C programming language is shown below.

TEST, RESULTS AND DISCUSSION

The technical analysis of this system requires a series of tests from the different stages of the system and the corresponding results. The following tests were carried out:

After the circuit design and drafting using the PROTEUS design software, the firmware for the Pic16F877A microcontroller, written in C-programming using the MPLAB integrated Development Environment (IDE), and compiled. This generates an HEX file, and the file is programmed into the microcontroller IC using the TOPWIN universal programmer.

Test /Responses

Proteus System Configuration:

- Power supply to the microcontroller stage: 5V
- Quartz crystal: 20Mhz

Test 1: Visual Simulation

Procedure: Press the play/simulate icon on the proteus simulation environment after loading the *cof/Hex* file into microcontroller IC.

Responses:

- oscillation frequency: 50Hz
- signal waveform: see fig xx below.
- system temperature: 28.0^{o}c
- load current:0.0A
- battery voltage:49.5V

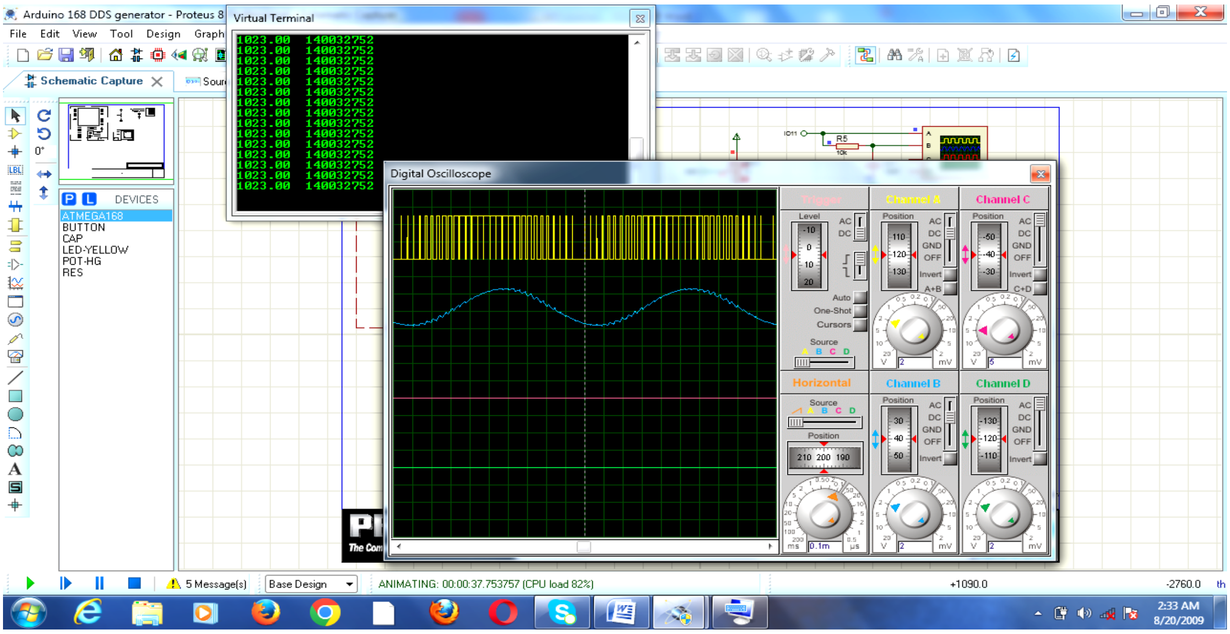


Figure 4: Simulation and Result

Test 2: Bread-Boarding

Procedures: The Hex file of the compiled programmed is written to the Pic16f877A microcontroller using a universal (TOPWIN) programmer, then the circuit components were mounted on a solderless breadboard following the designed circuit diagram.

Responses:

Using the oscilloscope and other measuring instruments the operating values were tested against the simulated values.

- oscillation
- frequency: 50Hz
- system temperature: 28.0oc
- load current:0.0
- battery voltage:49.5V

Test 3: Overall system Test/ Implementation

The figure below (fig 5) shows the wiring diagram of the complete system setup.

Test 4: Stare-Up/ No-Load Test

Procedure: the system is set up as shown in the diagram below and the power switch is turned on.

System Response on No-Load							
DC(Battery) Input voltage (V)	AC (output) voltage (V)	Frequency (Hertz)	System Temperature (°C)	Load current (A)	Power switch state	System fan state	Buzzer
49.6	220V	50Hz	31.7	0.0A	ON	Off	Off

Dummy loads	Power switch state	DC(Battery) Input voltage:	AC (output)	Frequency	Load current (A)	Temperature	System fan state	Buzzer status	System response/ status

		(constant)	voltage (V)						
Load at 20%	ON	48Vdc	219	50Hz	9.3A	39.1°C	Off	Off	normal
Load at 40%	ON	48Vdc	219	50Hz	19.1	44.8°C	ON	Off	normal
Load at 60%	ON	48Vdc	219	50Hz	30.8	50.5°C	ON	Off	normal
Load at 80%	ON	48Vdc	217	50Hz	38.6A	59.3°C	ON	Off	normal
Load at 100%	ON	47.2Vdc	221	50Hz	48.9A	78.7°C	ON	beep	warning
Load above 100%	ON	48Vdc	0.0V	**0Hz**	-	83.2°C	ON	Steady ON	Fault

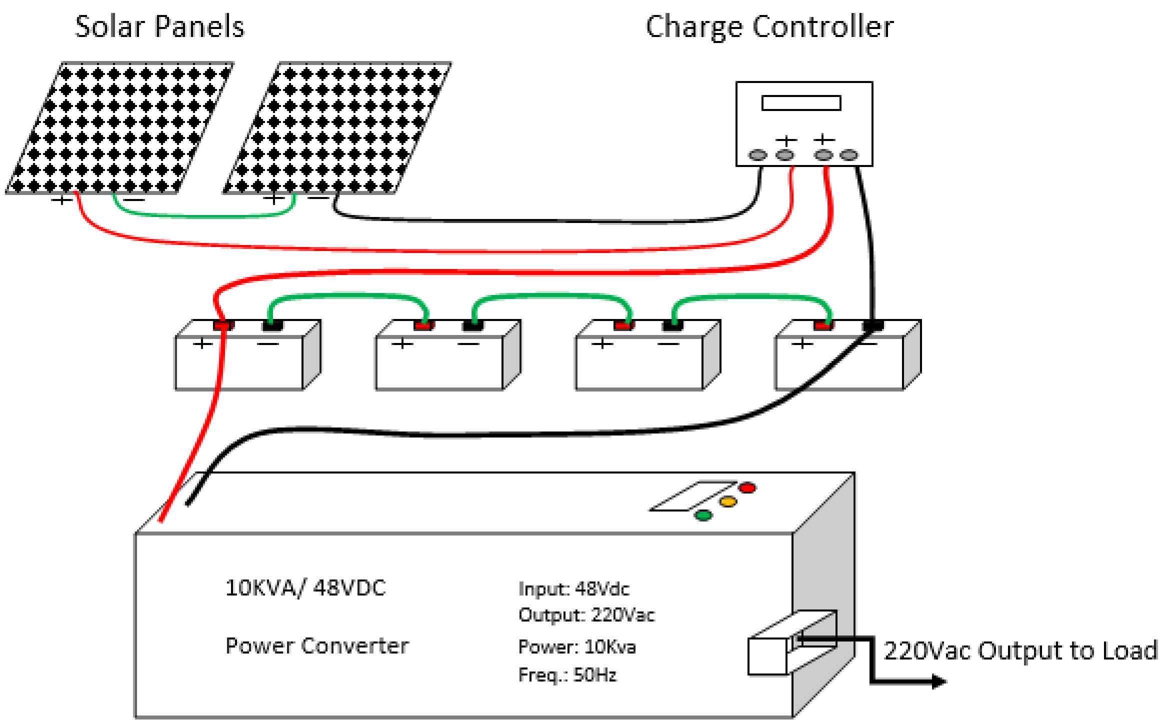


Figure 5: Final wiring diagram of system set up.

CONCLUSION

In conclusion, ferrite transformer-based converters play a pivotal role in advancing renewable energy applications. Their efficiency, compact design, and ability to operate at high frequencies make them well-suited for various renewable energy systems. As we strive for sustainable energy solutions, the utilization of ferrite transformers contributes to the overall effectiveness and viability of renewable energy converters, fostering a cleaner and more environmentally friendly energy landscape.

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