Design and Implementation of a Viable Power Inverter

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Abstract— in the last few years, people in the Gaza Strip started to rely on power inverters as part of a backup power system due to frequent failure of the mains utility. The simplest backup system consists of a battery, a battery charger, and an inverter. At least one house out of four in the Gaza Strip is equipped with such a system. In a previous work, a method for building a simple and applicable power inverter was presented. The used components and employed technology respect special conditions found in Gaza but also many other developing areas. However, the embedded battery charger is primitive and needs development. Moreover, the device has not been evaluated for induction motors loads such as fans or refrigerator compressors. In this work, the device charger is modified to run in a three stage charging algorithm. This is achieved by incorporating a TRIAC in the primary winding of the power transformer and controlling its firing angle according to the battery voltage as well as the charging current. Moreover, the inverter performance is investigated for running induction motors.

Index Terms— Power electronics, Inverter, Battery charger, PIC16F877.

I. INTRODUCTION

In the Gaza Strip employed inverters should generate an alternating voltage with a root mean square value of 220 V and a frequency of 50 Hz to meet the mains ratings. The primitive inverter produces a square wave output and the sophisticated one produces a sinusoidal waveform. The square wave inverter is simple and cheap but generates extensive fraction of harmonics which make it unsuitable to derive sensitive loads. On the other hand, the pure sine wave inverter is ideal but complicated and expensive. The modified sine wave inverter is a compromise; it reduces the harmonics significantly lending itself to drive most loads while being simple and efficient. The waveforms of these three types of inverters are illustrated in Figure 1.

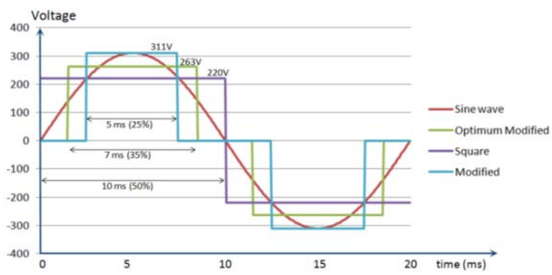

Figure1: Types of inverter output waveforms

The modified sine waveform is a square wave with gaps in between. The sine wave period is replaced by two square pulses whose amplitude equals the peak value of the sine wave ($220 * \sqrt{2} = 311$ V). The duration of each pulse is 5 ms which is one fourth the sine wave period. Therefore, the root mean square value (V_{rms}) of this waveform is identical to the sine wave. Drop in the battery voltage as well as increasing the load at the inverter usually lead to a drop in the pulse amplitude. Hence, the duration of the pulse is usually increased through an automatic feedback to maintain the rated V_{rms}. In [1] it has been shown that the minimum total harmonic distortion (THD) occurs when the pulse duration is about 35% of the pulse period.

It will be ideal if the backup battery is about 311 V DC. No need to step up or step down the DC supply. All needed is an H-bridge switching circuit to generate the modified sine wave [2]. However, for home use in the Gaza Strip where the inverter has a peak power less than 1KW, the backup battery is likely to be a 12V lead acid battery. With inverter efficiency about 85%, the full load DC current will be about 98A. Most commercial back up batteries in the Gaza Strip have a capacity above 150AH and have a cranking amps which exceeds the 98A. However, batteries perform best when charged and drained slowly. Therefore, for higher power inverters, it is more practical to use higher voltage battery banks. As an example, 2kW and 4kW inverters are recommended to run on minimum of 24V and 48V battery banks respectively which are still partial scale battery banks. For inverters above 5kw, one is advised to go directly for full scale battery banks (26 units in series making 312V DC bus). Inverter will be simpler, batteries will live longer, and overall power efficiency will be better.

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There are two alternative design approaches to handle low voltage batteries. The first approach is to convert the DC voltage to an alternating voltage of 50 Hz frequency and then use a step up transformer to convert it to the desired voltage. The other approach performs DC to DC conversion and achieves the full scale DC value prior to switching it at 50Hz by means of an H-bridge driver [3]. The second approach usually results in cheaper, smaller, and lighter inverters as it utilizes switched mode transformers. However, the first approach is more welcomed in the Gaza Strip due to the following reasons:

- The first approach uses one stage of switching electronics lending itself to be more reliable, easier to diagnose and simpler in maintenance.
- The power transformer used in the first approach provides DC-to-AC isolation and protects the transistors from damage. Therefore, it makes the unit more rugged and reliable.
- Classical power transformers needed in the first approach are manufactured locally with viable prices while switched mode transformers are not.

In a previous work the above mentioned circumstances are respected and a 1 KVA modified sine wave inverter running on 12V battery using the first approach is addressed [4]. The device works as battery charger when mains is available and is equipped with an automatic changeover relay to facilitate the operation of inverter mode and mains mode. Current and Voltage signals are monitored by PIC16F877A microcontroller and software is implemented to protect and control the operation of the device. The methodology presented in [4] is a compromise between the sophisticated approach presented in [5,6,7] and the amateur way presented in [8,9]. Although the device developed in [4] has an integrated battery charger, the charging algorithm is a primitive ON/OFF and lakes efficient utilization of lead acid batteries. The aim of this paper is to elaborate on battery chargers and enhance the battery charging method presented in [4]. The rest of this work is organized as follows: The original device structure is reviewed in section 2 while battery charging algorithms are presented in section 3. Details of the device modification are described in sections 4. Simulation and experimental results are presented in section 5. Finally in section 6, concluding remarks and an outlook of future work are given.

II. DEVICE ARCHITECTURE

The inverting circuitry is composed of four sections; the push-pull signals generator, the MOSFIT power drivers, the power transformer and the regulation feedback section as illustrated in Figure 2. The device functions are controlled by PIC16F877 microcontroller as shown in Figure 3.

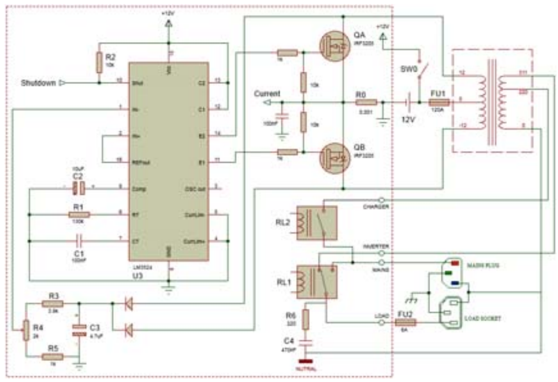

Figure 2. Device main components

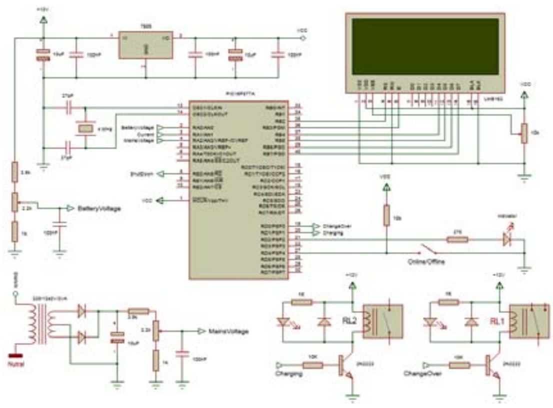

Figure 3. Device controller

The power transformer is custom made 12x2/311V/1KVA. It has a 220V tap that will be connected to the mains during battery charging mode. The PWM generator depends on a voltage feedback signal in order to adjust the pulse duty cycle so that regulated output voltage is generated. The main reasons of voltage variations are:

- Decrease of the battery voltage as battery gets discharged.
- Drop in the internal resistance of the battery and MOSFETs especially under heavy loads.
- Drop on the transformer windings.

The most correct method to acquire the feedback signal is using a low rated transformer to step down the output voltage. The output transformed voltage is rectified, filtered, and conditioned by a proper voltage divider as illustrated in Figure 4. The value of the capacitor (C3) is critical. Small values will cause high ripple in the sense signal while high values cause delay in the feedback loop. This leads to severe oscillation in the root mean square of the output voltage specially when running refrigerators. A time constant of the RC combination from 50 to 100 ms is found to have excellent performance. Therefore, with 7.1KΩ voltage divider, a 10μF capacitor is selected. For analysis of these types of feedback control problems one may refer to [10].

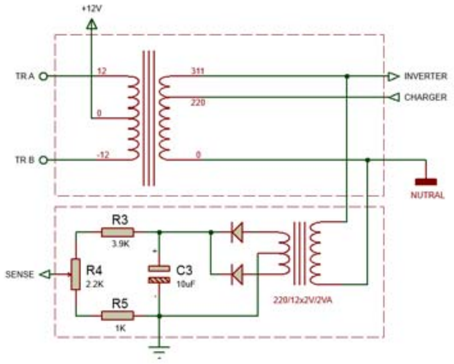

Figure 4. The power transformer and the feedback

One may acquire the feedback signal from an additional 12V windings included in the power transformer as illustrated in Figure 5.

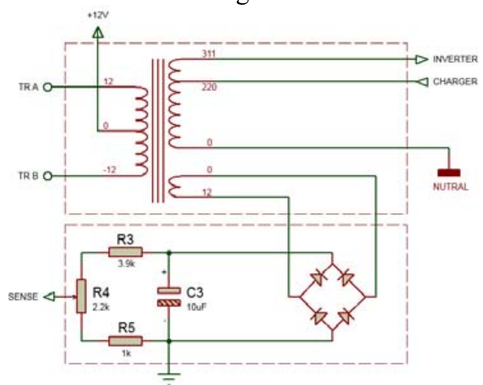

Figure 5. Feedback using additional winding

The feedback method presented in [4] is based on reading the DC level on the primary winding. The three feedback methods have been implemented and evaluated and it is found that the first approach yields the most regulated output (220±7V) while being the most complicated. On the other hand, the last approach is the simplest while yielding the worst - but yet tolerable - regulation (220±15V). Due to its simplicity, compactness, and cost effectiveness, this novel method is recommended.

III. BATTERY CHARGING

The single stage charger connects a rectified power supply to the battery till its voltage reaches a threshold value (V_{boost}). Current is not controlled in this primitive algorithm and batteries are charged to less than 70% if charging duration is less than 5 hours. Full level of charging may be achieved in case of slow chargers for which the charging process continues for more than 16 hours.

The two-stage charger adjusts the charging voltage in the first stage to keep a constant preset charging current (I_{start}). The value of this current is set between 10% and 30% of the battery capacity. The first stage is terminated when the battery voltage reaches the V_{boost} threshold. The duration of this stage is about 5 hours when the battery is initially fully discharged. In the second charging stage the charging current is reduced gradually to keep the battery voltage at V_{boost}. This continues till the rate of change of the current approaches zero. Practically, this point is identified when current drops to a preset value (I_{end}) which is about 3% of its initial value. The buttery now is fully charged and should be disconnected. The expected duration of this charging stage is another 5 hours. One should highlight that lead acid batteries must not remain at the peak voltage for too long. Manufactures specify the maximum allowable time around 48 hours.

The three-stage charging algorithm has an additional stage for self discharge compensation. The charging current is adjusted to keep the battery voltage at a preset value called V_{float} as illustrated in Figure 6.

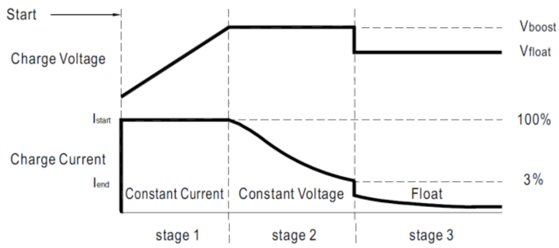

Figure 6. Three stage charging algorithm

Values of the threshold voltages V_{boost} and V_{float} are critical and they are usually specified by the manufacturer along with the recommended current settings. Ranges of these thresholds for a standard 12 volt 100 AH lead acid battery are summarized in Table 1.

Table 1. Ranges of preset voltages.

	minimum	typical	maximum
V_{boost}	13.8 V	14.4 V	14.7 V
V_{float}	13.5 V	13.6 V	13.8 V
I_{start}	10 A	20 A	30A
I_{end}	0.1 A	0.5 A	2A

Although lower threshold values lead to longer charging time, they insure maximum service life of the battery [11].

IV. CHARGER MODIFICATION

The original battery charger was a simple on/off one controlled by means of a relay (RL2). This relay connects the mains supply to the 220V windings. The 12V windings of the transformer become the secondary windings and the induced voltage is rectified by means of the body diodes of the MOSFETs as illustrated in Figure 7. Battery charging is switched off once its voltage reaches 14.4V. It is activated again when the battery voltage drops to 12.2V.

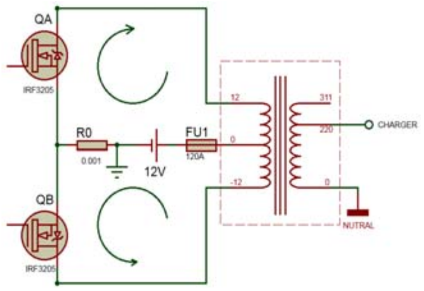

Figure 7. Charging current loops

The charging relay is replaced by a TRIAC as illustrated in Figure 8. The battery enters the charging process during the conduction phase of the TRIAC in which the mains supply is switched to the 220V windings as illustrated in Figure 9. The induced voltage which determines the charging current is controlled through setting the firing angle of the TRIAC.

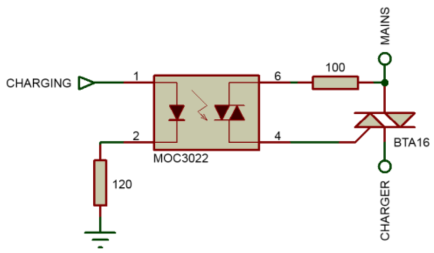

Figure 8. Triac interfacing

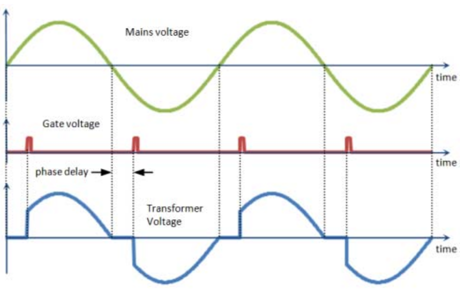

Figure 9. Phase angle control

The microcontroller circuit is updated to detect the zero-crossing of the mains voltage as illustrated in Figure 10. This enables synchronizing the firing pulses generated by the microcontroller with the mains supply. For each zero crossing event of the supply voltage an interrupt is triggered. The service subroutine sends a firing pulse after a specific delay to the charging digital output. The duration of each firing pulse is about 0.5 ms which is sufficient to trigger the triac on. The triac is a latched device and stays on until the next zero crossing when current tries to reverse its direction.

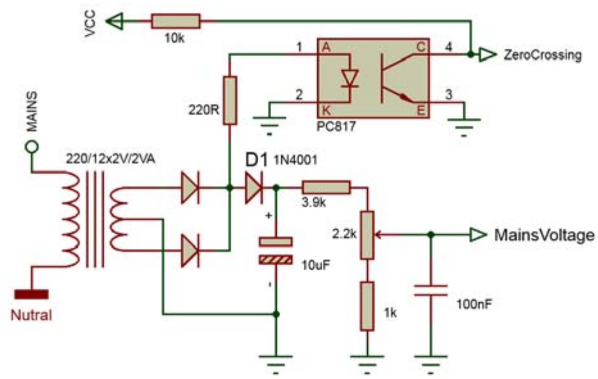

Figure 10. Modified AC mains sensing

The phase delay is automatically adjusted to fulfill the three stage charging algorithm. This algorithm requires the charging current information. Therefore, the current sensing circuitry is modified as illustrated in Figure 11.

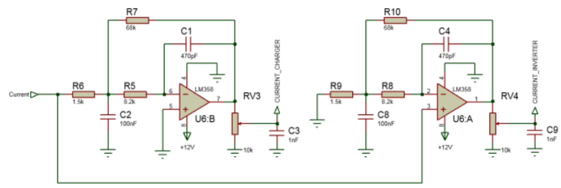

Figure 11. Current signal conditioning

The LM358 integrated circuit contains two independent, high gain, internally frequency compensated operational amplifiers which were designed specifically to operate from a single power supply over a wide range of voltages. One Op-Amp is configured as inverting DC amplifier to condition the battery current signal during charging for interfacing to the microcontroller analog input AN3. The other Op-Amp is configured as non-inverting DC amplifier and utilized to magnify the battery current metering signal during inverting mode. This enhances the resolution of current measurement and overload setting. The resultant modified device controller hardware is shown in Figure 12.

In software implementation, the 10 ms period of the trigger signal is quantized to 500 cycles which is approximately the time to execute the command

```
for (i=0;i<500;i++){;}
```

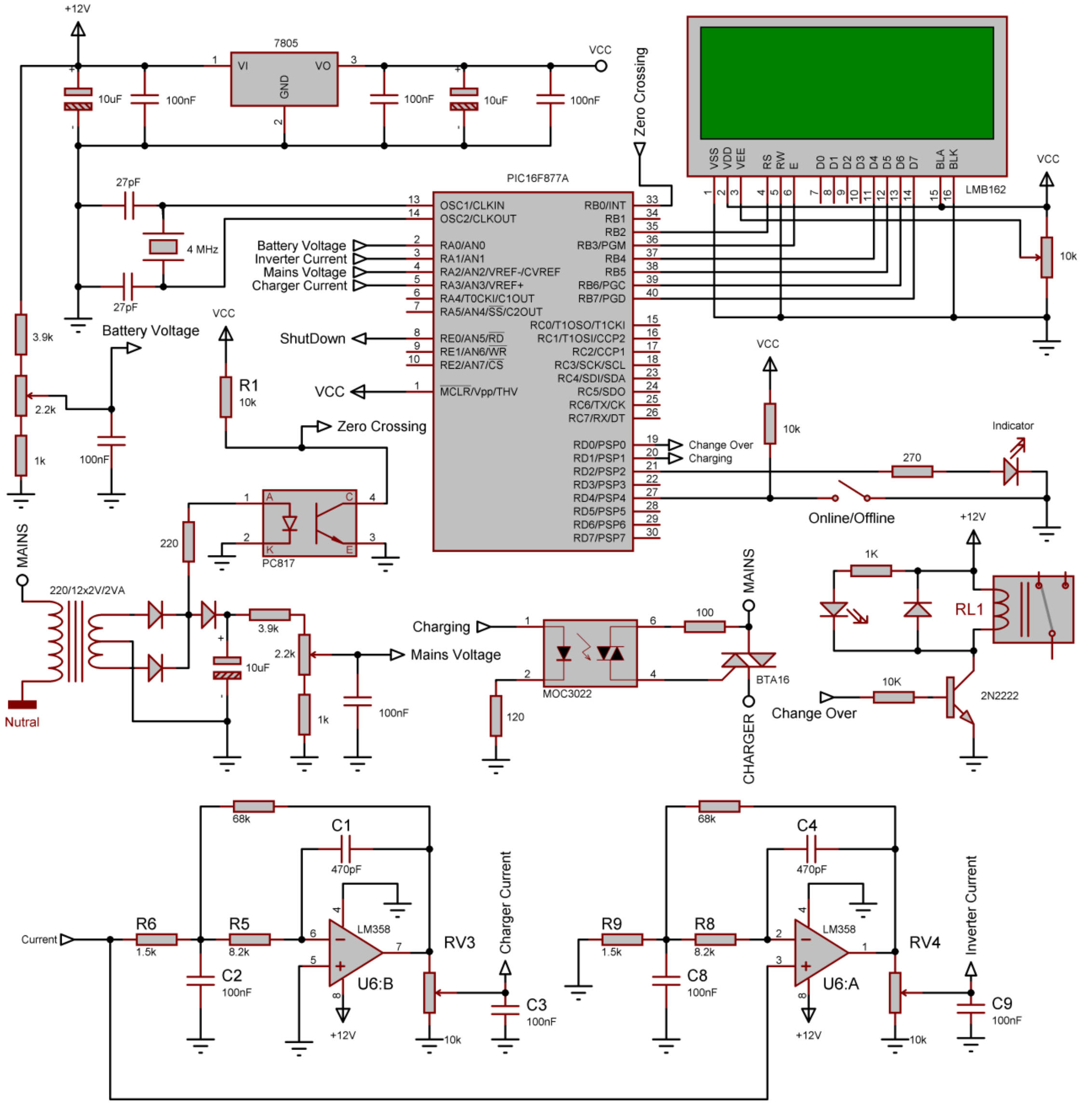

Figure 12. The modified controller circuitry

An integer global variable (PhaseDelay) is defined to hold the required phase delay. This variable is used by the interrupt service subroutine to generate the corresponding trigger pulse as follows:

```
void interrupt()
  {
     for (j=0;j<PhaseDelay;j++){};
     PORTD.F1=1;
     for (j=0;j<25;j++){};
     PORTD.F1=0;
     intcon.intf=0;
  }
```

A program segment in the main subroutine continuously updates the value of the PhaseDelay variable as illustrated in Figure 13.

V. SIMULATION AND EXPERIMENTAL RESULTS

The original device is first investigated for running induction motors. The starting current of induction motors may be as high as 5 times its rated current; even if its power factor is compensated. The inverter is 1KVA rated but is expected to withstand 2KVA transient surge for few seconds as its MOSFET drivers were oversized. It is found that a 0.5HP drill whose power factor is modified to be close to unity starts safely on the inverter and works regularly. On the other hand, a refrigerator motor was more challenging as it has the compressor load at starting. Moreover, its auxiliary winding is resistive; leading to a very high current peak

```
ChargerStatus=0;
PhaseDelay=Tmax;
intcon.gie=1;
while (1)
{
  Analog= ADC_read(0);
  DCV = 0.9 * DCV + 0.1 * 16.0*Analog/1024;
  Analog= ADC_read(3);
  ChC = 0.9 * ChC + 0.1 * 25.0*Analog/1024;
  Analog= ADC_read(2);
  ACV = 0.9 * ACV + 0.1 * 260.0*Analog/1024;

  if (ACV<150 || ACV>250 ) // AC mains failure
  {
    intcon.gie=0;           // disable interrupts
    break;                  // quit the charging mode
  }

  if (ChargerStatus==0)     // constant current mode
  { if (DCV>Vmax) ChargerStatus=1;
    if (ChC < Imax & PhaseDelay>Tmin) PhaseDelay-=1;
    if (ChC > Imax & PhaseDelay<Tmax) PhaseDelay+=1;
    Lcd_Out (2,1,"constant 20A mode ");
  }

   if (ChargerStatus==1)    // constant voltage mode
  { if (ChC<Imin) ChargerStatus=2;
    if (DCV < Vmax & PhaseDelay>Tmin) PhaseDelay-=1;
    if (DCV > Vmax & PhaseDelay<Tmax) PhaseDelay+=1;
    Lcd_Out (2,1,"constant 14.4V mode");
  }

    if (ChargerStatus==2)   // floating mode
  { if (DCV<Vmin) ChargerStatus=0;
    if (DCV < Vmid & PhaseDelay>Tmin) PhaseDelay-=1;
    if (DCV > Vmid & PhaseDelay<Tmax) PhaseDelay+=1;
    if (PhaseDelay>=Tmax) intcon.gie=0; else intcon.gie=1;
    Lcd_Out (2,1,"floating 13.6V mode");
  }

    if (ChC>1.1*Imax)      // Overload protection
  {
    intcon.gie=0;
    Lcd_Out (2,1,"Charger Overload !!");
    while (1) {;}
  }

  print_MM();              // display readings on the LCD
}
```

Figure 13. Part of the main subroutine controls the phase delay

during startup. In [12] and [13] a valuable discussion and tricks for running refrigerators on inverters. In summary, one should use an oversized inverter while the motor has to be compensated to relief the inverter from unnecessary reactive current and protect the MOSFETs from voltage spikes. For our experimental testing, an old fridge whose motor is rated 1/3HP run successfully on the inverter. Figure 14 illustrates the output waveforms for different levels of power factor correction.

The voltage spikes due to inductive load may damage the transistors. Usually freewheeling diodes are employed especially when BJTs are used for switching. For most MOSFETs, they have integrated freewheeling diodes. Additional freewheeling Schottky diodes may be connected anti-parallel to the transistors as illustrated in Figure 15. These diodes cannot be connected anti-parallel to the primary windings in the same manner a freewheeling diode is connected to a relay coil or a DC motor. This would damage the transistors immediately. The transformer is an active devise; if a voltage is applied on one of its primary windings during a half cycle, a voltage is developed on the other primary winding. Therefore, if a freewheeling diode is connected anti-parallel to one of the transformer primary winding banks to protect its switching transistor will be forward biased causing a short circuit while the other bank is switched on.

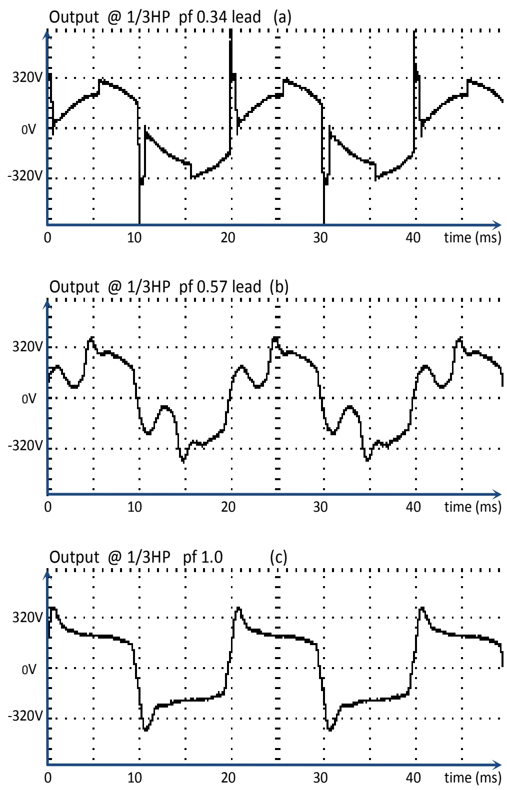

Figure 14: Output waveforms with a Fridge motor at different levels of power factor.

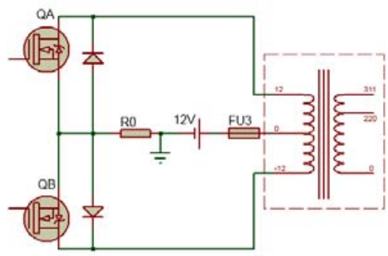

Figure 15. Additional freewheeling diodes

The way freewheeling diodes are functioning is not well described in the literature for this inverter type and it deserves detailed clarification here. A diode connected anti-parallel to a transistor bank will not conduct neither when this bank is switched on nor switched off. However it serves for freewheeling to the other transistor bank. Assume that bank A is switching off, the voltage spike starts to build on bank A windings and its negative will be developed on bank B due to the magnetic coupling. This continues till the spike amplitude reaches the battery voltage. At that instant the freewheeling diode of bank B conducts seizing the spike. The loop resistance of bank B kills the spike on bank A as well. Remember that a resistance is transferred from one winding of a transformer to the other winding with the square of the turns ratio.

The modification modules for upgrading the device to incorporate the designed three-stage charger have been implemented and tested successfully for operation. Then, the improved printed circuit board of the device is designed, realized, and validated. Figure 16. shows the board before plugging the LCD, heat sinks, and the 0.001Ω resistor.

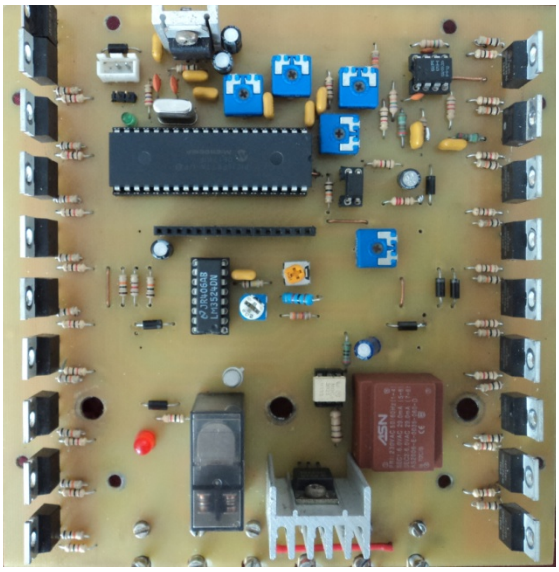

Figure 16. The improved printed circuit board

During software validation, simulations using the Proteus simulation tool have been conducted. Unfortunately, there is no available model for lead acid battery in this tool; therefore, its behavior is simulated manually by means of two potentiometers which specify its charging current and voltage status.

Farther simplifications were necessary in the simulation circuit due to frequent timing errors and excessive CPU loading events. Figure 17 shows the simplified circuit used to simulate the charging routine while Figure 18 illustrates a resultant set of waveforms. The power supplies P1 and P2 are 180° out of phase sinusoidal signals with 50 Hz frequency. The interrupt signal ZC is a 100 Hz clock synchronized with P1 or P2. The 'mark' time of this clock signal is specified 0.5ms while its space 'time' is 9.5ms.

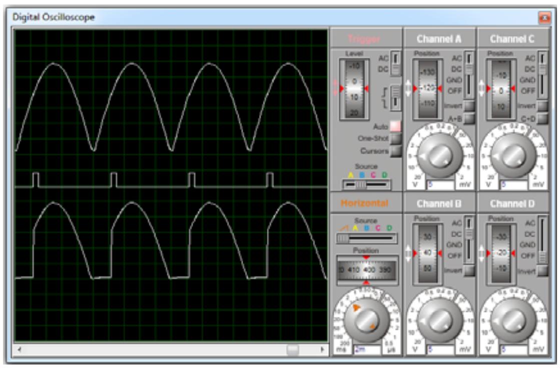

Figure 18. A resultant set of waveforms.

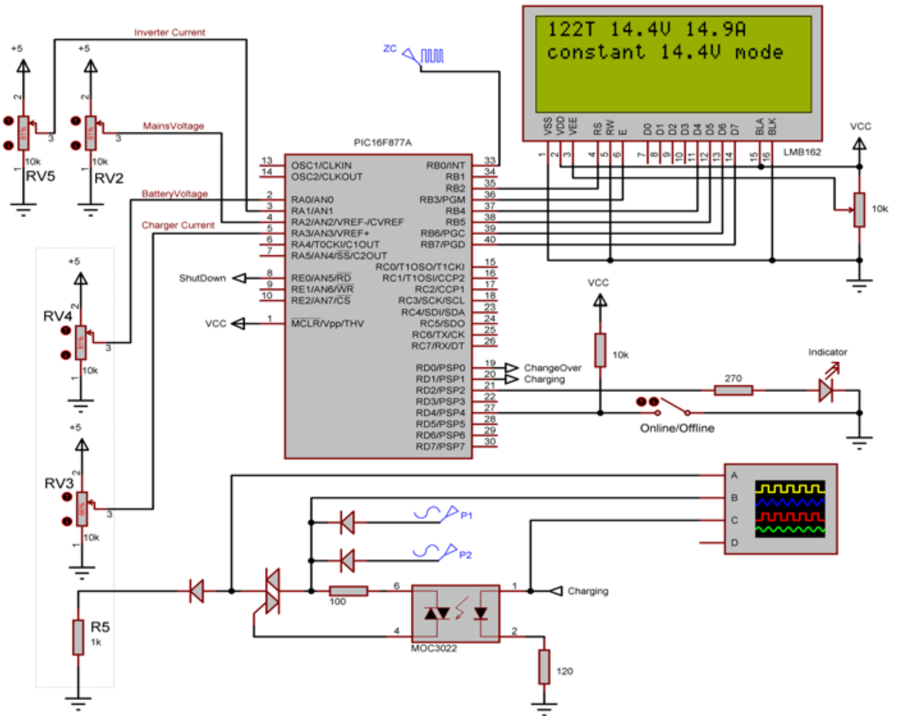

Figure 17. Charging algorithm simulation circuit.

VI. Comments and Outlook

This work presents development of a 1 KVA modified sine wave inverter. The used components and employed technology respect special conditions found in Gaza but also many other developing areas. The design methodology and practical results described in this manuscript may serve also as a valuable tutorial for electrical engineering students as it utilizes knowledge of many subjects.

It is found that induction motors run on this inverter given that its rating do not exceed 1/3 the inverter rating. Moreover, it is strongly recommended to compensate the power factor of these motors before connecting them to the inverter.

In the near future, the developed device is planned to be implemented in a compact commercial shape. Also we plan to implement a maximum power point tracking (MPPT) solar charger using the same technology.

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