SPWM Power Inverter with ATtiny25
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1. Basic idea and requirements

This is a project about a sinusoidal pulse width modulation (spwm) power inverter “update”. The topology selected for this project is push-pull, by means that the output is equally driven by the power stages (a semi-period by each stage) - although spwm inverters are usually based on full-bridge topology. The basic requirements:

a. Output RMS voltage 220 Volt AC (more on this later)

b. Frequency of the output signal 50Hz

c. Total RMS power by the inverter 300 Watt (more on this later)

d. Input Voltage 12V DC

e. Sine wave output waveform (more on this later)

Although 300 Watt RMS power selected for this project, the general terms and functions are the same for any power desired (more details will be presented during this project in order one will be able to construct the same project with more power).The reason of 300 Watt is that I already have an 24 VDC / 230 VAC 750Watt RMS Power inverter in my lab constructed a long time ago (in 2002) and I had build another inverter, the 48 VDC / 220 VAC 1500 Watt Sine Wave Inverter using Hexfet* transistors, presented a long-long time ago (in 1997), as a project in graduating from Technological Educational Institute of Athens and get my diploma. Because that one constructed then and after a while disassembled, this smaller inverter is the “reincarnation” of the older one, following the same principles that I used in that project (although with totally new approach). Also I've built a 12 VDC/230V AC 300Watt push-pull power inverter with modified square wave output (in 2003), which is the one that will be “updated” (although still working fine as it is). Whenever you see in the text “old brother” or “older inverter” or any similar, it is referred to the 1997 sine wave one (whose the basic principles will follow). 230VAC or 220VAC where referenced are the same (I have a 2x9V/220V transformer, but now 230V AC became the standard voltage in Greece, but loads can work with either of them).

The reason for presenting this one, is because it's smaller and easier to build. Previous inverters had at first uncontrolled output voltage, updated later (in 2012) for automatic control by manually setting the desired output voltage. Why follow principles of 1997 you may ask? That project was awesome for it's time, for me, gave me a grade of perfect 10 and why not? Principles are still the same...I'm a principal guy!

Hexfet was a trademark of International Rectifier (1997), now acquired by Infineon Technologies

2. Basic calculations and a little info

a. Maximum Power and current

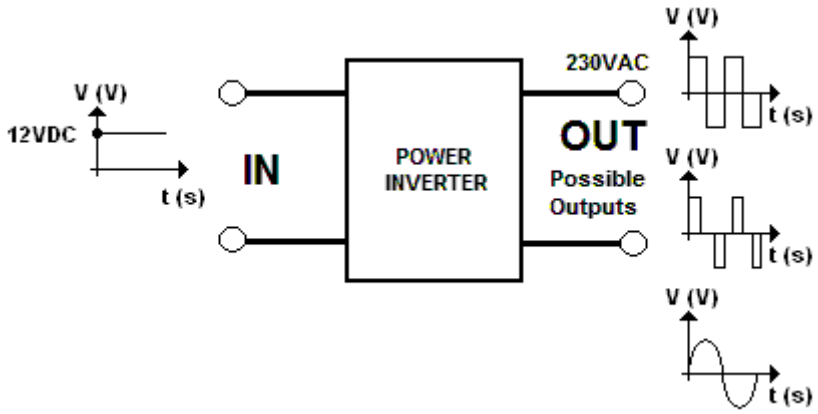
The inverter will be powered by 12 Volt direct current voltage provided from batteries. Let's calculate the maximum currents (for DC and AC Side):

P = V*I and P_{MAX} = 300 Watt , V_{DC} = 12 Volt , so I_{DC} = 300W/12V = 25 A
On the AC side we have P = 300Watt and V=230V, so I_{AC} = 1,30 A

Given the above results, the fuses that we will use to protect each side, are:
1) 25A - 30A Fuse (Fast) on the DC side
2) 1,5A - 2 A Fuse (Fast) on the AC Side.

b. Operation and waveform

The operation of this inverter (and any other despite the topology) lies in the principal that when a direct current voltage source, driven to a switch-mode circuitry, produce an alternative current voltage source. To conform with the specifications stated on (1) the voltage must be stepped-up in order to produce the 230Volt output we need. The following diagram shows that principle [the 230Volt shown on the output is the RMS value (the peak values for each waveform are different)]:



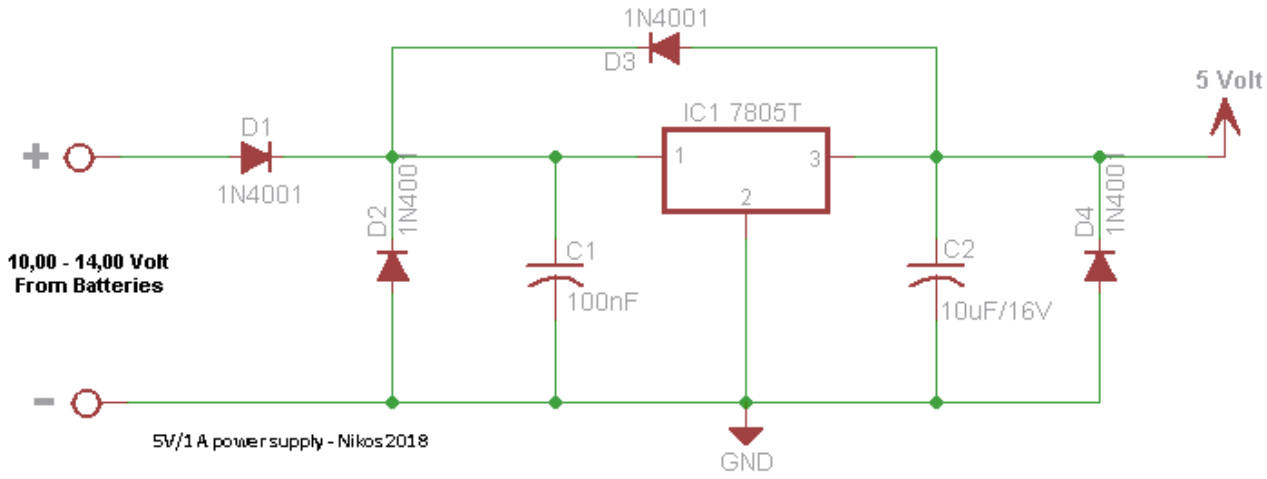
For this project, the driving scheme selected is the Sinusoidal Pulse Width Modulation (spwm). This technique produces less harmonic distortion than the standard Modified Sine Wave (or Modified Square Wave – MSW as I like to call it), usually harmonics are in the higher end of the frequency spectrum of the carrier signal, thus filtering is easier (smaller components and values). The stepping-up of the voltage will be done by using a power transformer (which will also provide isolation), in this case a 2x9V/220V/600 Watt (2 primary windings of 300Watt each, which is the cost of the push-pull topology in comparison to the H-bridge inverters that use single primary winding). Because at that time (1997) Hexfet Power Mosfet were relative new components and very expensive here in Greece, it was better to create a push-pull topology, instead of purchasing 4 Hexfet for full-bridge (and many more because some would blow-up during the various tests... Back then the power transformer was a “beast” having specifications 2x40V/220V/3000Watt). Given the fact that the 2x9V/220V/600W transformer already exist (so no added cost), push-pull topology was a one-way road...

3. Circuits and components used

a) DC Input Voltage and power supply

The battery (or batteries) that will be used in this project, must provide the inverter with the necessary power. The type can be SLA, GEL or any other type. Voltage of these batteries can vary depending on their charged state. Under normal conditions, the voltage in open circuit must be > 12.50 V (when fully charged with 2,275V/cell – at 13,65V) down to 11,80 Volt or less. When discharged, can reach 10,50V (ending discharging point at 1,75V/cell for SLA type – or lower to 10,00Volts or less for other battery types). The operation is the same, the charging process is slightly different between for the different battery types (each manufacturer gives the details for their batteries).

Given the above situation, the power supply of the inverter can be constructed using everyday components, found in anyone's self. A simple circuit diagram of the power supply of this inverter is presented below:



All schematics were made by using Bsch3V by H.Okada(Suigyodo) (c)1997-2014 , hitoshi@suigyodo.com for contacting the author.

The above circuit is straightforward, a typical 7805 circuit with further protection. I used Texas Instruments LM7805 IC and it will be referred that way through this document, as well as any other IC used in this project. D1 is used to protect the circuit if polarity is reversed and diode D4 is used to protect the LM7805 if the output is shorted (providing a return path for reverse currents). The D3 diode is protecting the LM7805 the same way for as the D4 and “takes” the reversed currents together with D2 to provide the return path to reverse currents. The two capacitors used, input 100nF to provide the LM7805 with filtered input and C2 for output (value 1uF to 10uF (or larger) to fit the requirements. In the final PCB the simple version used (with not all protection).

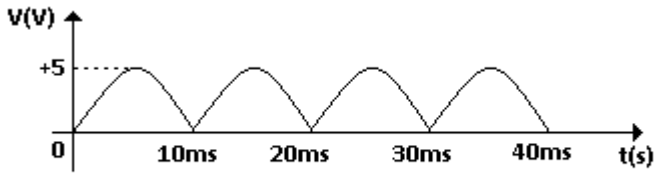
The “old brother” used a power supply circuit build around a Simple Switcher© LM2576HV step down switching regulator capable of providing 3A output current. This project does not have the same power requirements, so a simpler circuit is built (you can use a variable regulator - LM317 or similar instead of LM7805). Also the old one had 48V DC input voltage (and thus working with the HV version of LM2576), here only 12V DC will be the DC input voltage.

Simple Switcher was a trademark of National Semiconductor (1997) - now Texas Instruments after acquisition

b) Sine and Triangle signals and production of spwm signal

In order to produce an spwm signal, a sinusoidal waveform and a triangle waveform (of the same max and min amplitudes for best results) must be compared. The product of this comparison, the spwm signal which will be used in driving the power stages. For the sine and triangle reference waveforms, the older brother used two Intersil ICL8038 analog function generator chips. This one will be build around a microcontroller, thus saving space, specifically a Microchip's AVR© 8bit RISC MCU (based on a modified Harvard architecture), that will be programmed to perform the necessary functions. These micros can be programmed in Assembly, C, Pascal, Basic and others as well. Usually for such projects I prefer the Assembly language (although a little more messy and time consuming to do the programming)

In the older inverter, a nice trick was used... Instead of comparing a full period of the reference sine-wave, only a semi-period was used and later “replicated” as it is symmetrical. To accomplish that, the sine waveform was rectified and thus producing the following waveform (as shown a double-frequency waveform produced (100 Hz), but this was not a problem since the distribution circuits for the power stages used a 50 Hz reference signal, thus re-creating the correct sequence.

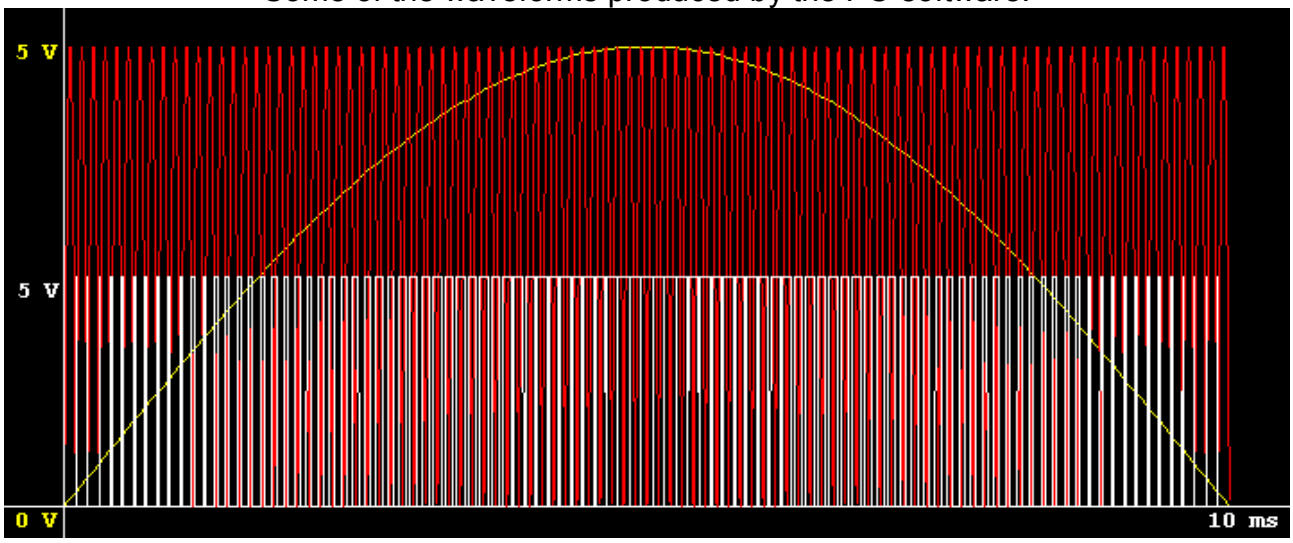


100Hz rectified sine waveform

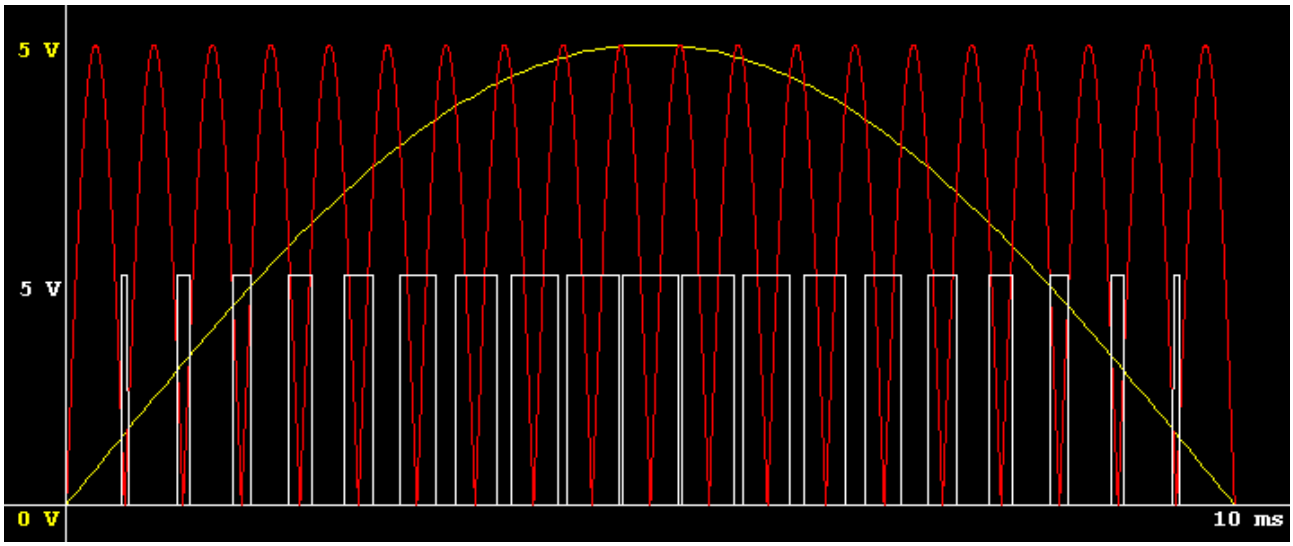
The new version will use an MCU... Of course the same principal can be applied here also by means to produce the sine waveform (usually by using a lookup table), pass it through a R-2R circuit, filter it out, produce the triangle waveform the same way, produce the 100Hz and 50Hz square reference waveforms etc etc etc. To produce the sine-wave (at least to a good fidelity) a lookup table for at least 8 bits is needed and the more the better. For the triangle also about the same stuff and not to mention that the automatic voltage control will be implemented in the MCU as well, so probably these are too many jobs to do with this MCU (or at least too many jobs for me to do with this MCU).

So, in order to have the MCU do less jobs (and write less in the firmware) a “good trick” was used... The sine and triangle waveforms instead of the MCU, were both produced by a PC-Software of mine, the comparison made by the same software and the product of this comparison (the spwm signal) was produced also there... The times that the square waveform changes from 0V to 5V and from 5V to 0V were recorded on a table for further processing. The more high the triangle frequency, the more the comparisons needed and the lower the triangle frequency, fewer comparisons will be made. If instead of triangle a high frequency sine waveform is used, yields to the same results (more or less – depending on the frequencies ratio).

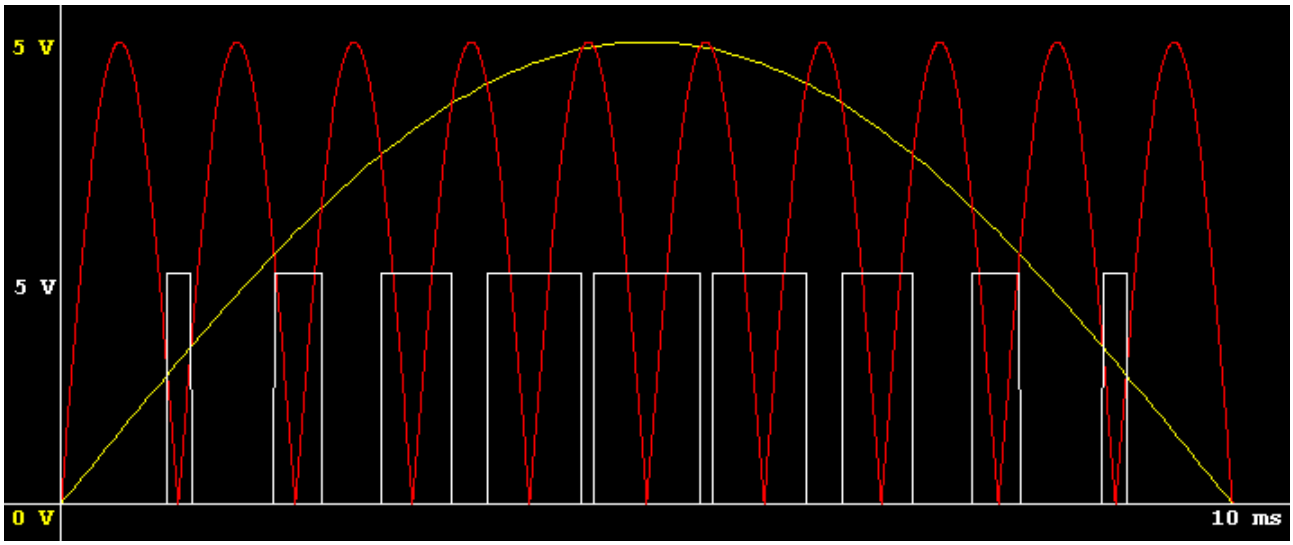
Some of the waveforms produced by the PC-software:



100Hz and 10kHz results



100Hz and 2kHz results



100Hz and 1kHz results

The above figures show how the spwm signal is produced by comparing the reference and the high frequency sine waveform. The amplitude of the spwm signal is +5V (it is shown to have half the amplitude for cosmetic reasons - to be able to distinguish the changes more easily). The old brother used two comparator circuits build around LM311 voltage comparators, having the sine waveform in the non-inverting (+) input and the triangle waveform in the inverting input (-).

With the above technique there is no need for negative power supply, which would be necessary if it was to compare a full-period (non-rectified) sine wave with the corresponding triangle wave. Also the comparators circuits and power stages would need this negative power supply to distinguish the signals, so space and complexity saved at the same time.

Since microcontrollers have less processing power than computers, another trick was used... After finding the times of the comparisons, the table of values was further processed based on the clock frequency of the MCU calculating the ratio of the MCU clock versus comparison time. Since the output signal is in milliseconds (we want 50 Hz output) and the MCU clock usually is in nanoseconds (usually > 1MHz), the duration of transitions was recorded. Further more another bunch of calculations made in accordance to Timer prescaler, in order to decide which Timer (and with what prescaler) is better to use and how many interrupts would occur per period. The selected Timer will be configured for interrupt on overflow. The table shown below is for 100Hz and 1kHz waveforms for **MCU_{CLK} = 2 MHz**

Idx	Time (s)	spwm (V)	Duration (µs)	MCU Clock	MCU Clocks	Tmr8 (250 kHz)	Tmr64 (31.25 kHz)	Tmr256 (7.812 kHz)	Tmr1024 (1.953kHz)
1	910 µs	5 V	910 µs	500 ns	1820	228	28	7	2
2	1113 µs	0 V	203 µs	500 ns	406	51	6	2	0
3	1820 µs	5 V	707 µs	500 ns	1414	177	22	6	1
4	2222 µs	0 V	402 µs	500 ns	804	101	13	3	1
5	2727 µs	5 V	505 µs	500 ns	1010	126	16	4	1
6	3335 µs	0 V	608 µs	500 ns	1216	152	19	5	1
7	3637 µs	5 V	302 µs	500 ns	604	75	9	2	1
8	4445 µs	0 V	808 µs	500 ns	1616	202	25	6	2
9	4547 µs	5 V	102 µs	500 ns	204	25	3	1	0
10	5455 µs	0 V	908 µs	500 ns	1816	227	28	7	2
11	5558 µs	5 V	103 µs	500 ns	206	26	3	1	0
12	6365 µs	0 V	807 µs	500 ns	1614	202	25	6	2
13	6668 µs	5 V	303 µs	500 ns	606	76	9	2	1
14	7275 µs	0 V	607 µs	500 ns	1214	152	19	5	1
15	7780 µs	5 V	505 µs	500 ns	1010	126	16	4	1
16	8183 µs	0 V	403 µs	500 ns	806	101	13	3	1
17	8890 µs	5 V	707 µs	500 ns	1414	177	22	6	1
18	9092 µs	0 V	202 µs	500 ns	404	51	6	2	0
19	10000 µs	0 V	908 µs	500 ns	1816	227	28	7	2

Table 1 – Calculations for 1 kHz spwm signal for f_{MCU} = 2 MHz

The last entry is to complete one semi-period (output is still 0V during this time, so no transition is made). All values were rounded to the nearest integer (% of error is negligible). “Typical” prescaler values used, although some Timers on AVRs have also 16, 32 and other prescaler settings, but since many values can do the job, no need to over-calculate ! All other tables for the frequencies used are calculated in the same way. It is easily seen that prescalers 256 and 1024 can't be used for the selected MCU clock frequency, since there are too few ticks per interrupt, so one of the others will be used.

The final decision was made to use the **prescaler value = 8** (for 250 kHz timer frequency) for the 1 kHz spwm signal. **Timer0** will be used and configured to generate an overflow interrupt for the spwm signal generation and **Timer1** will be configured to generate an overflow interrupt for each semi-period (every 10ms). **Timer1** will be configured for **prescaler = 256** (thus 7812.5 Hz frequency). To generate an overflow interrupt need 78 "ticks" (because 78 * (1/7812.5) = 9.984ms). The period **T_{TMR1} = 2 x 9.984ms = 19.968ms** or **F_{TMR1} = 50,08 Hz** which is what we want to produce (with % error approximately 0,16% which is practically nothing...) and so **the start-up value of Timer1 will be 255 - 78 = 177 (or $B1 in hexadecimal).**

After prescaler selection, a new table was constructed in order to find the start-up values of Timer0. Because Table1 display 'clock ticks' needed by Timer0 to reach the desired time, there is no need to have the mcu do the calculation, we will calculate the actual values needed to load Timer0 to perform the counting. The values to load Timer0 are calculated as 255 – value as with Timer1 (both are 8-bit counters)

Idx	From (s)	To (s)	Duration (µs)	Output (V)	MCU Clocks	Timer0 Ticks (CLK / 8)	Timer0 Startup Value
1	0 µs	910 µs	910 µs	0 V	1820	228	27
2	910 µs	1113 µs	203 µs	5 V	406	51	204
3	1113 µs	1820 µs	707 µs	0 V	1414	177	78
4	1820 µs	2222 µs	402 µs	5 V	804	101	154
5	2222 µs	2727 µs	505 µs	0 V	1010	126	129
6	2727 µs	3335 µs	608 µs	5 V	1216	152	103
7	3335 µs	3637 µs	302 µs	0 V	604	75	180
8	3637 µs	4445 µs	808 µs	5 V	1616	202	53
9	4445 µs	4547 µs	102 µs	0 V	204	25	230
10	4547 µs	5455 µs	908 µs	5 V	1816	227	28
11	5455 µs	5558 µs	103 µs	0 V	206	26	229
12	5558 µs	6365 µs	807 µs	5 V	1614	202	53
13	6365 µs	6668 µs	303 µs	0 V	606	76	179
14	6668 µs	7275 µs	607 µs	5 V	1214	152	103
15	7275 µs	7780 µs	505 µs	0 V	1010	126	129
16	7780 µs	8183 µs	403 µs	5 V	806	101	154
17	8183 µs	8890 µs	707 µs	0 V	1414	177	78
18	8890 µs	9092 µs	202 µs	5 V	404	51	204
19	9092 µs	10000 µs	908 µs	0 V	1816	227	28

Table 2 – Calculations for start-up values of Timer0 for 1kHz spwm

ATtiny25 is equipped with 128 bytes of internal non-volatile eeprom and 128 bytes of internal volatile static ram. It has also 2 kbytes of non volatile program flash memory, so the necessary time-values will be stored in one of these memory spaces. It can be configured for internal clock or external clock, external crystal or resonator. The clock that will be used **is external crystal at 2.000 MHz** because I have many available from past projects (any other crystal can be used as long as the calculations will be done for that clock frequency), along with two 22pF ceramic capacitors. The internal fuses of the MCU were programmed as: **CKSEL [3:0] = 1010** for external crystal or ceramic resonator (0.9 MHz to 3.0MHz) and the Clock Divide by 8 fuse (**CKDIV8**) was **disabled** (un-programmed to 1). Please note! In AVR microcontrollers fuses '0' means programmed whilst '1' means un-programmed.

ATtiny25 has six programmable I/O lines on PORTB (PB0 to PB5), where PB5 will be used as $\overline{\text{RESET}}$ and the rest for the various functions. The port-map of the microcontroller used in this project is presented below:

Port pin	Function / Description	Direction
PB0	SPWM Signal for channel #1	OUT
PB1	SPWM Signal for channel #2	OUT
PB2	ADC1 input for automatic voltage regulation	IN
PB3	XTAL1 for 2 MHz crystal	IN
PB4	XTAL2 for 2 MHz crystal	IN
PB5	Used as $\overline{\text{RESET}}$ (user configuration doesn't mind)	IN

In the next chapter the automatic voltage regulation will be analyzed, along with some more information about the microcontroller.

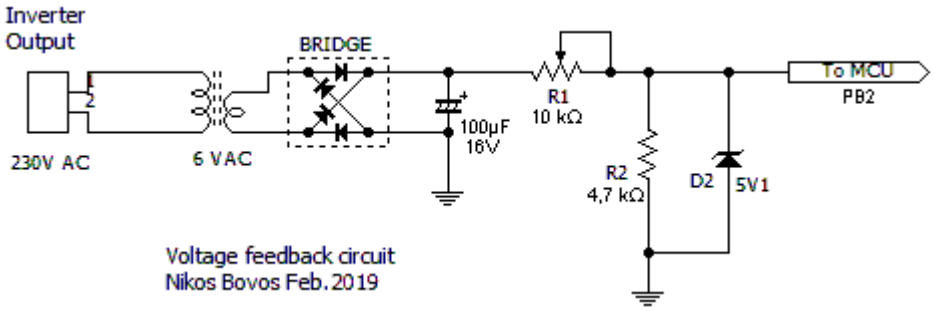
A must-say note! *Although no code accompany this document, the guidelines and information provided here are more than enough for anyone with "typical knowledge" to build this project and adjust it for his/her own needs. Because I spent too much of my – not so free - time to construct, write, build, test, update etc I'm awfully irritated when I'm asked to provide the full listing for "copy & paste" from others. I'm sorry to say that, but buying 2 boards, connect them with 2 cables and writing two lines of code to your computer does not help you in any way to learn how and more important why it works (even if that LCD screen is displaying 'Hello world !')...It's better to try and fail and then to repeat until you get it and learn a lot in the process, than to get the "working code" from others without even scratching your brain on how to do it.*

c) Automatic output voltage regulation (AVR)

This project will have the ability to stabilize the output RMS voltage to the 'desired' value (here 220V AC). The existing MSW inverters I've built, do the same, according to the selection of the user (by using a potentiometer in the front panel), so they can theoretically produce output values from 0V to 300V (although 99% of the times they've been used for 220V AC output RMS voltage whenever a utility black-out occur). This is accomplished by varying the duty cycle of the MSW signal (modified square wave – suitable for 90% of the devices at home - or modified sine wave as the advertisements like to refer to it). In this project regulation will be done automatically (no user intervention).

Unfortunately, it is “forbidden“ to touch the duty cycle of the signal - as it is not a MSW signal, so there are really only two available options. The first is to modify the peak voltage of each pulse (by using multiple windings in output transformer or variable DC input) and the second is to modify the frequency of the pulses of the spwm signal (which is what we are going to do, since the existing transformer will be used).

Before entering to this, a little more information about how the automatic voltage regulation will be done... In the output of the inverter, a simple circuit built to reference the output voltage, as shown in the following schematic:



Not much to over-analyze for the above circuit... Output is stepped-down by a PCB-transformer to "MCU-acceptable" levels. Then rectified, filtered and then it is divided by the voltage divider that consisted by resistors R_1 and R_2 and then driven to the ADC input of the MCU (to PB2 input as shown on the port-map before). The Zener diode is there to protect the input pin of the MCU if the input voltage exceed 5,1 Volt (which is nearly impossible for the current setup). The above circuit was adjusted to provide to the MCU pin V_{PB2} = 3,003 V, when the output voltage is 220V AC. The capacitor's value (68µF - 100µF) selected is one that is not too big to loose small changes of output voltage, nor too small to have rippling (and give wrong results - the A/D of MCU has a very good resolution). A good test is to measure with oscilloscope/voltemter the rippling to find the golden rule . A table of values could be constructed with the levels of the output rms voltage versus the corresponding A/D values, but it's easy to calculate for yourself.

In order to automatically regulate the output voltage, it's unrealistic to stick to 220V RMS voltage (although not impossible since A/D has good resolution). A realistic approach is to define a "safe window" of acceptable voltage (and regulate when voltage is outside this window). The margin chosen is 4 Volt (nearly nothing), so we will accept output voltages for RMS values between 218-222 Volt (or 228-232V for 230V output). We are not trying to create a "stabilizer" here, but to have a voltage source that can be used with the loads we have at home (although still not impossible for smaller "window").

ATtiny25 features a 10-bit successive approximation Analog to Digital Converter with 4 single ended channels (or 2 differential channels) and temperature measurement capability. ADC1 input (PB2) will be used to measure the input signal from the feedback circuit. For single-ended channel 10-bit resolution the result is given by:

$$ADC = \frac{V_{IN} \times 1023}{V_{REF}}$$ (datasheet states 1024, but result is 1023 (1024 are the A/D 'steps'

from 0 to 1023). Highest ADC result is $3FF = 1023 (1024 minus one LSB) and lowest result is $00 (as with all 10bit A/D converters). The reference of the ADC was selected to be $V_{REF} = V_{CC}$ = 5V and so for 10-bit resolution each ADC measurement 'step' will be 5V / 1024 = 4,88mV (for 5.00V power supply). For the selected voltage window, we calculate minimum and maximum acceptable values as **ADC_{MIN} = 2,974V** (this is translated by A/D as $261) and **$ADC_{MAX}$ = 3,027V** ($26C). So we will have a safe window of $26C - $261 = $0B or 11 A/D 'steps'. The previous values were setup to microcontroller to be compared with the result of the A/D conversion. If more or less safe window needed, the above values can be changed accordingly.

The A/D converter was setup for prescaler = 32 (by setting ADPS2=1, ADPS1=0, ADPS0=1 in ADCSRA register) thus having clock with f=62,5 kHz. Each conversion according to the datasheet takes about 13 ADC clock cycles (after the first conversion), or about 200 μs. The A/D converter configured for free-running mode (bits ADTS2=0, ADTS1=0, ATDS0=0 in ADCSRB register). The first A/D conversion however must be started by the user by setting ADSC bit in ADCSRA (using *sbi ADCSRA, ADSC*)

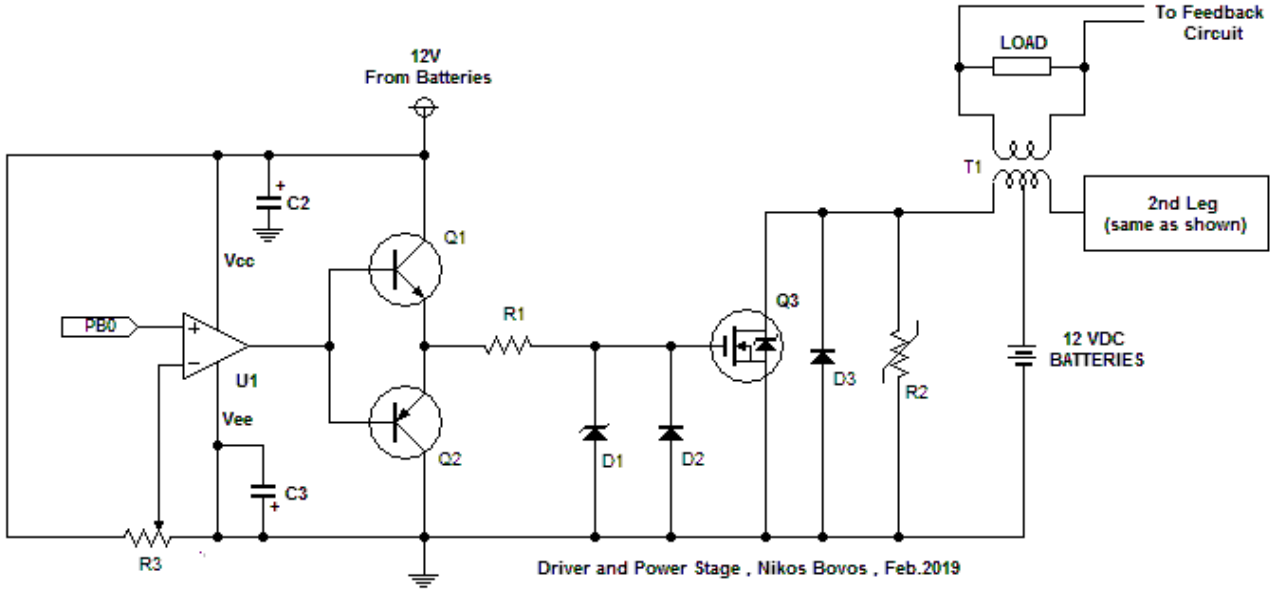
To be able to regulate the output voltage, in each period of the output signal the A/D is comparing the ADC result to the maximum and minimum values setup on the mcu (this is done about every 100 A/D conversions or 20ms). As stated before, we can't touch the duty cycle of the spwm signal and must stay in that form in order to reproduce a sine wave in the output, so the realistic approach is to change the driving scheme with higher frequency when we want lower output voltage, or lower frequency when we want higher output voltage (and always keep the spwm form of driving). The value from ADC used, is the full 10-bit (could also use 8-bits, by setting ADLAR=1 in ADMUX I/O register and read ADCH register value only, but didn't need that, so the full 10-bit result is processed).

On previous page, the table of the values for one driving scheme (spwm for 1kHz) is shown. For the current setup (battery, transformer, Hexfet etc) **six of these tables defined, from 400Hz to 2000Hz** to fit various loads and saved in flash memory of the MCU. For your setup maybe a different frequency scheme might be needed... To do the automatic output voltage regulation, the mcu start from the highest frequency (which gives the lowest RMS output voltage) and then switch tables according to the result of the A/D comparison (or stays on the same table if the output voltage is within the accepted limits). One final note, is that the prescaler of Timer0 is changed according to the driving scheme needed (because for every table a different Timer0 prescaler value is needed, for instance 1 kHz spwm driving need prescaler = 8, while 600 Hz need prescaler = 64). **One last note**, if the lowest frequency (400Hz) fail to have the output voltage within the limits, then the mcu automatically switch to 50% and 60% Modified Square Wave (MSW) driving as on the existing PCB and fall back to SPWM driving when “allowed”. Why higher spwm frequency produces lower voltage? Because on-times of pulses are smaller than in MSW and so the total Root Mean Square (RMS) value is lower.

d) Drivers and output power stages

<u>Another critical note!</u> *The "comfort zone" of 5V low current mcu environment is long gone here If you plan on building this project. Extra care must be taken, high currents are produced in this part of the project, capable of doing damage ! Use adequate cables and connectors and take all safety measures (even wear protective glasses when lean above to work on these PCBs. Any mistake or short-circuit will "kill" components instantly spreading their pieces around. Double-check everything before power up! Please don't mess with this, if you are not 100% sure of what you are doing !*

The spwm signal produced by the MCU is at a voltage level capable of driving logic-level Mosfet transistors, but not at necessary power for fast switch-on. Because the existing boards of the MSW inverter will be used, the following is the existing circuit from 2003 (which have standard level Hexfet Power Mosfet Transistors).



A few words about the above circuit...U_1 is a LM311 voltage comparator that produces +12V from +5V input pulses. R_3 variable resistor set a low voltage (~ 300mV) on the non-inverting input to avoid the possibility of oscillation when both pins are 0 volt - due to the high open gain of the comparator. Transistors Q_1 and Q_2 form a 'totem pole' with low impedance output path. These are switching transistors (BD239 and BD240 but any pair of NPN/PNP switching transistors can be used capable to charge Mosfet's C_{ISS}). Transistor Q_1 drives the Hexfet Power Mosfet Transistors, whereas Q_2 provide a return path for reverse currents (can be omitted if you trust the two diodes speed) when Q_3 is switching-off and driving signal is 0 volt. R_1 is typical < 10Ω providing a low impedance path to Mosfet's Gate. D_1 is a 12V Zener diode to protect Mosfet's Gate from over-voltage (by not allowing voltage to exceed maximum V_{GS}). D_2 is a fast recovery small signal diode (1N4148 or similar) and provide a return path of induced currents by the Source. Q_3 is consisted of two IRFP250 Hexfet Power Mosfet transistors connected in parallel (each one is 30A/200V), whereas D_3 is an 60EPU02 Ultrafast Soft Recovery Diode (60A/200V). R_2 is a varistor (V130K14) protecting the D-S junction of the Mosfets (clamping excessive induced voltages to about 170V DC) and finally transformer T_1 is the existing center-tapped 2x9V/220V/600Watt. Bypass capacitors are 0,1μF/16V tantalum or similar for all ICs used. The other leg not shown is exactly the same, only the input to comparator is from PB_1 pin of the microcontroller.

Since we are using a push-pull topology, all references are to the common ground (the battery '-') so there are no floating parts - as with full bridge circuits where the upper leg components are at the output voltage level and thus need a bootstrap / driving circuit. Here a simpler driving scheme is used. The above circuit has proven to be very robust all these years, whenever it had (and has) to operate. The big brother 24V/750Watt also uses the same circuit for each leg but with different components. An optional R-C or R-C-D snubber circuit can be used (aiding the Mosfet Transistors at switch-off with typical values 33-47 Ω and capacitor of 10nF) placed in parallel to the D-S junction. "Usually" for all other Mosfet circuits are omitted except for chopper applications. For the existing boards, no snubber circuits exist, without any problems with various types of loads (at least so far...).

If higher output power is desired, output power transformer and Mosfet transistors need to be changed accordingly and the protective diodes if existing ones are not sufficient. Cables and connectors also to handle the necessary current (usually I use larger diameter cables and connectors, to avoid any voltage drop and heat on the cables and to be sure that they can withstand more than the current needed by the application, so most of the times when upgrading a circuit it's not necessary to change the cabling).

A quick note about the external anti-parallel ultrafast recovery diode... Power Mosfet Transistors have an anti-parallel diode build-in in it's body. Usually (and this depends on the application) it's a good practice to have an external diode to increase the protection level. For instance, the internal diode of IRFP250 has reverse recovery time of max. 280ns (IRF datasheet). If this is not enough (high dv/dt exist, an ultrafast (35ns) external diode is used. Newer Mosfet have faster and more robust characteristics for their internal diode and capabilities - check with datasheet – here the old 2003 circuit is used so these information apply and the external diodes were mandatory.

A quick note about filtering... spwm is multi-pulsed-signal so you need to filter the voltage waveform. Usually an L-C filter designed for 1/10 the carrier frequency of spwm signal will give enough attenuation to the higher order harmonics. More later...

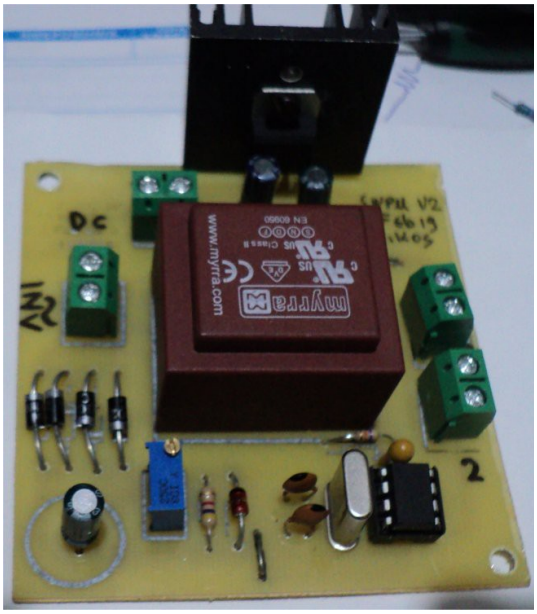
A quick note about Mosfet voltage selection. Even though we have "only" 12V input DC voltage, on inductive loads (and the power transformer is an inductive load for the Mosfet transistors) induced voltages occur at switching times (at turn-off). These can be as large as 10 times or more the switching voltage, thus the Mosfet transistors selected have V_{DSS} = 200V. If any 40V or 50V Mosfet were used, probably they would be destroyed relatively quick after power-up. In general, for switching applications is a good practice to select components with capability to withstand 10 times the switching voltage – although we use a varistor for protection, sometimes they are not "quick enough" for the dv/dt of the induced voltage. Again, newer components have better characteristics and protections, see their datasheet, but in general it's a good practice to select components with maximum ratings higher than the ratings of the application (a little more costly but surely worth it to save the most expensive components).

A quick note about transformer selection. This is a small headache, because the “correct” transformer depends on the spwm carrier frequency. Unfortunately for my setup I had available the 2x9V/220V for the MSW so I stick to that. A greater ratio i.e 2x6V/220V would allow higher driving frequencies and thus smaller filters, but this was available to work with so a few compromises made...

4. Construction and testing

a) The PCB of the project

One printed circuit board constructed to update/replace the existing board that has the power supply, the mcu and the feedback circuit. The output and power PCBs already existed and used, as the rest device (there is also a battery charger circuit board that charges the battery from mains – whether the inverter is operating or not, when the machine is connected to mains power supply, but it is out of the scope of this document). A "quick and dirty" PCB was made having dimensions 74mm X 74mm. The older one (based on the AT90S2313 microcontroller – and still working like a charm - for the MSW driving of the output stages was a little bigger 100mm X 74mm) because also had a second MCU, an ATtiny13 to perform the A/D work for automatic voltage regulation and battery-low control (by using 2 A/D channels of ATtiny13 and signaling the main MCU with 2 pins (4 possible situations for lower MSW, higher MSW, in the set-point MSW and low battery signals), but due to lack of extra free pins in ATtiny25 the battery-low function didn't implemented in this board... A thought was to discard the external crystal, use the internal one and use an I/O pin for the battery control, but since most of the time battery-low does not occur (power outages don't last long and the battery to power this inverter is a 12V/60Ah battery, holds quite good for all the necessary time of inverter operation (4 and more hours). If in the future this arises as a need, the above possibility will be examined. The battery-low is easier to implement, since only one point of interest is set-up (the voltage for battery-low) and then after 5 or more successive battery-low A/D measurements the MCU cut-off the driving of the output stages (this is not done in the 1st measurement, as many inductive loads can signal a battery-low at startup). Each A/D measurement was taken every 1 sec. Don't ask why 2 MCUs were on the same board (instead of a single MCU with A/D), the original board had AT90S2313 only for the MSW driving and then placed ATtiny13 as an "add-on" to the existing board and the firmware of AT90S2313 was updated accordingly...



The "updated" PCB Version 2
Original(1997) PCB was a 2-sided, 210x297mm PCB (including power stages)

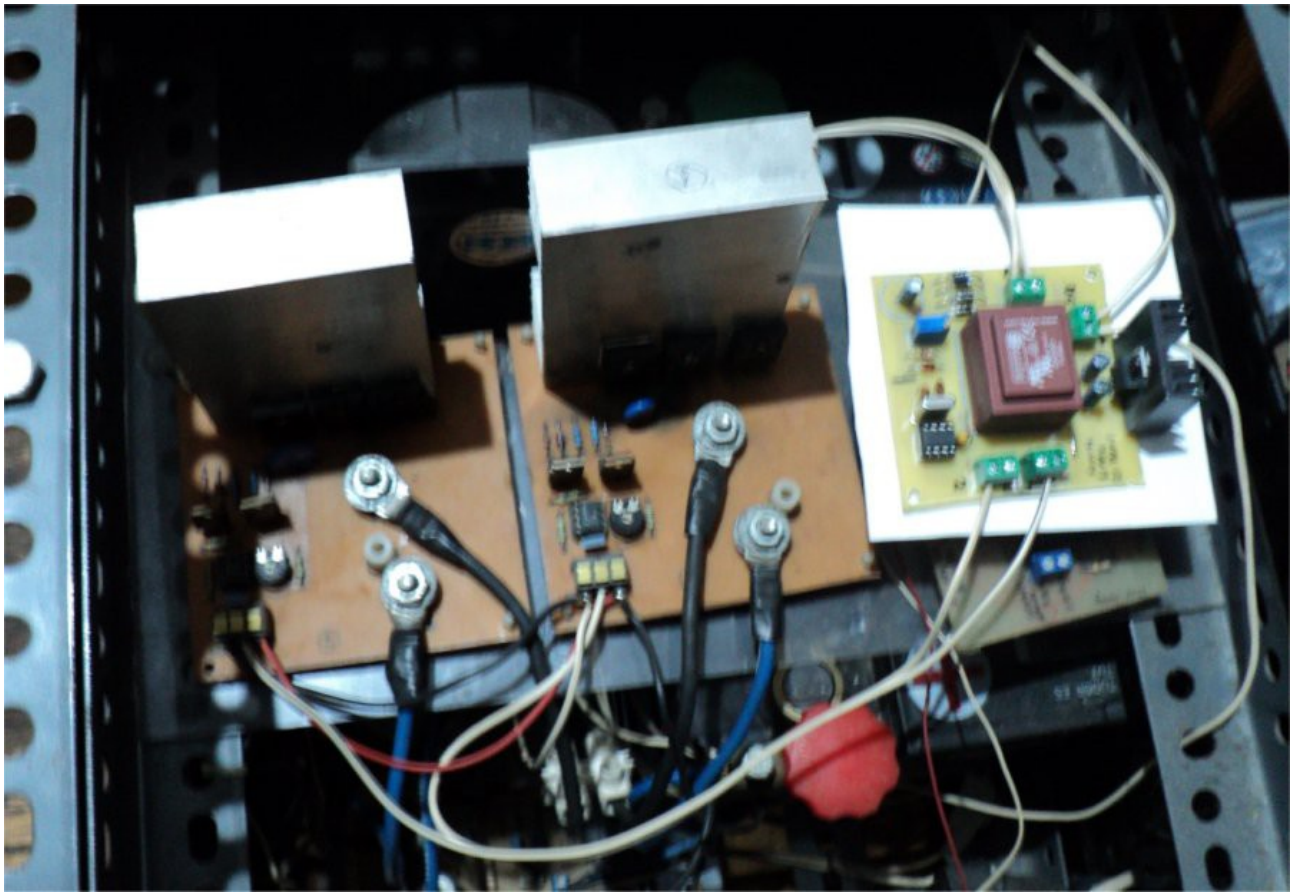
b) Waveform filtering

As stated, SPWM signal is a multi-pulsed signal so it must be filtered out in order to be accepted by the loads. The "old brother" used 30 kHz carrier for the spwm signal and the filtering was done in the input (primary of the transformer), by constructing two “big” air inductors of 330μH each, with wire capable of delivering 35A and it was a real challenge to make them (the transformer primary usually has low inductance value compared to the much higher inductance of the secondary)... The capacitors used were 33μF non-polarized, thus giving two low-pass filters (one for each leg) with cutoff frequency (-3db) approximately f=1,5 kHz. The output waveform was a good sine-wave with low THD (the attenuation on the 30kHz carrier was more than 100db) and transformer noise was eliminated.

In this setup, unfortunately the carrier frequency is much smaller (MSW 50%, MSW 60% and SPWM 400Hz up to 2kHz) and I didn't want to challenge myself again with even bigger inductors in the primary this time, so the filtering was made in the secondary of the transformer, sacrificing the "transformer noise" and sacrificing a little of the efficiency also. Because of the secondary big inductance (> 10H) only a capacitor filter placed in parallel to the secondary winding. After a few tests, the finalized value is 10μF (composed by 10 capacitors of 1μF/630V polyester non polarized, connected in parallel). For this period and the available time that I don't have, it's more than fine... Either way, I wanted to experiment more on the waveform and the automatic regulation, than to have the cleanest sine wave in the output (not impossible though if you can wind the needed primary air-core inductors).

c) Installation and tests

The board installed and inverter powered-up for load = 100 Watt (30%).

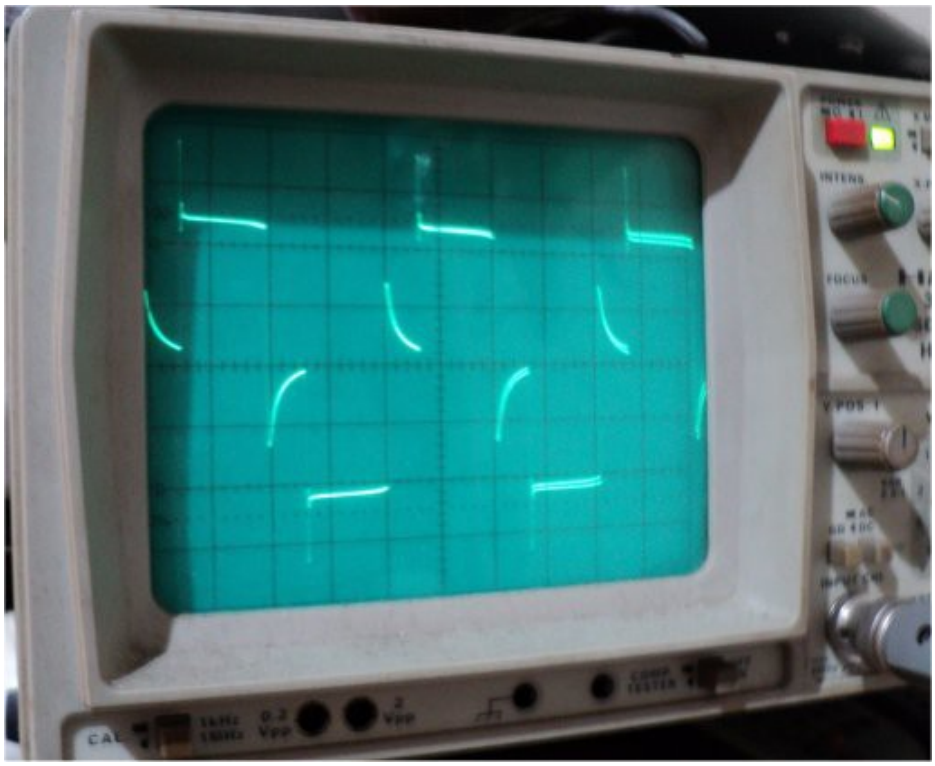


The board is sitting on top of the existing one. Apart from the new board, the two output & power stages are shown. Behind the two heat sinks there is a 12V DC fan, the battery is shown under the boards on the right is a car battery 12V/60Ah). The output transformer is in the left-back side and not shown. In the bottom is just visible the battery charger circuit. The "big cables" connect the Drain of the parallel Mosfets to Transformer primary winding and the Source to battery negative (ground). The high current connections as seen is made with nuts and bolts... Overall it's a heavy metal construction (exceeding 20 kg, since the car battery itself is > 10 kg) and it is placed on four wheels for easy transportation whenever is needed to operate.

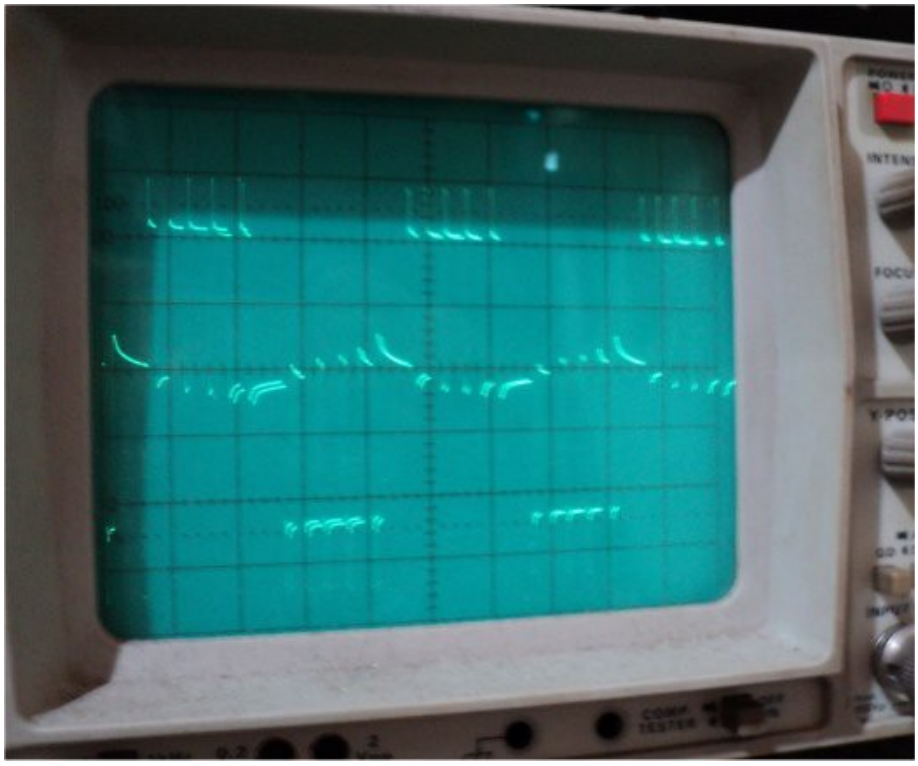
For 100 Watt load, the waveforms of the old PCB and the new PCB were "taken" (photographed), with and without output filtering. The tests that conducted were for filtering by the (total) capacitor of 10μF.

For the MSW inverter this filter smooths too much the waveform, whilst without filter is the classic MSW waveform (the MSW driving is done a 50 Hz only and you can't hear the transformer). In the spwm driving PCB filtering is mandatory because otherwise the waveform can't be used with normal loads (a photo was taken also). All photos were taken for 220 – 230VAC. The "noise" of driving is audible.

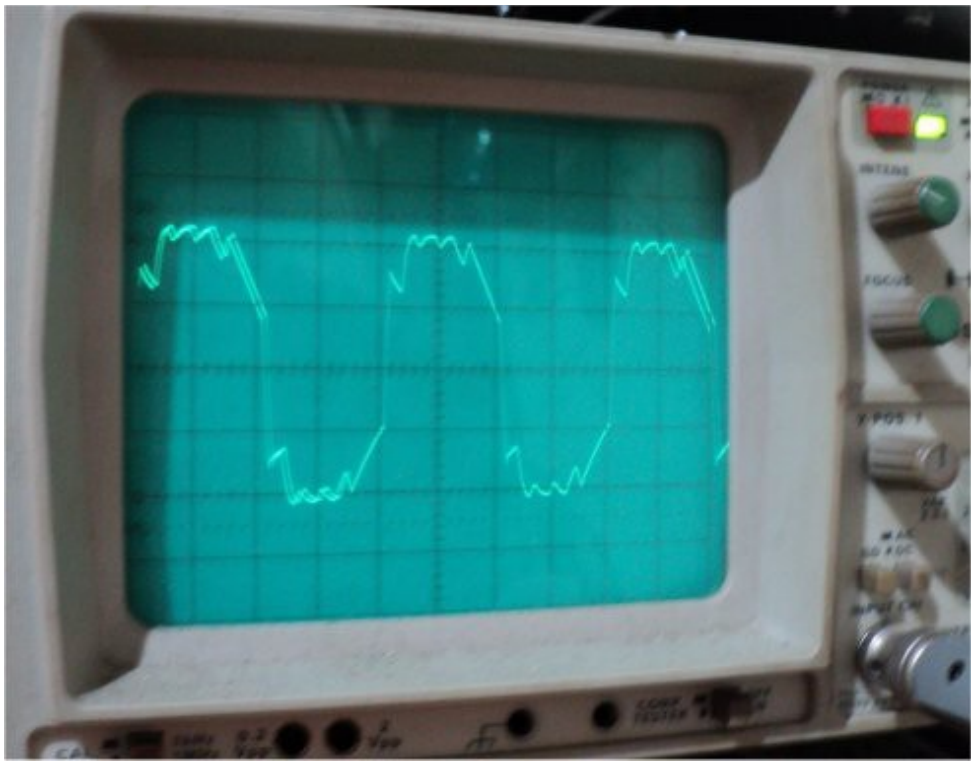
The oscilloscope (a Hameg 303-4) was setup for 5ms/div on X-axis and 100V/div on Y-axis (10V x10 on probe). The output frequency of the signal was measured at 50 Hz by a multimeter and on the screen of the oscilloscope. Load on all photos is 100W (30%).



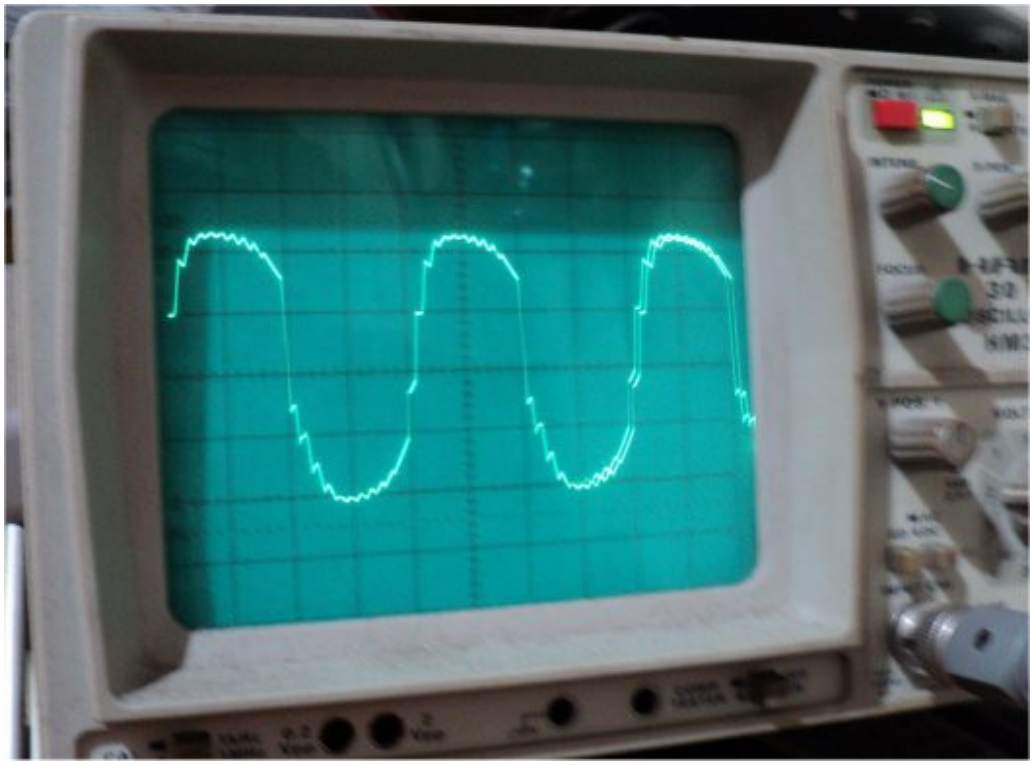
The old "standard" 50Hz MSW (no filter) of the old PCB
(the above is for Duty Cycle approximately 70%)



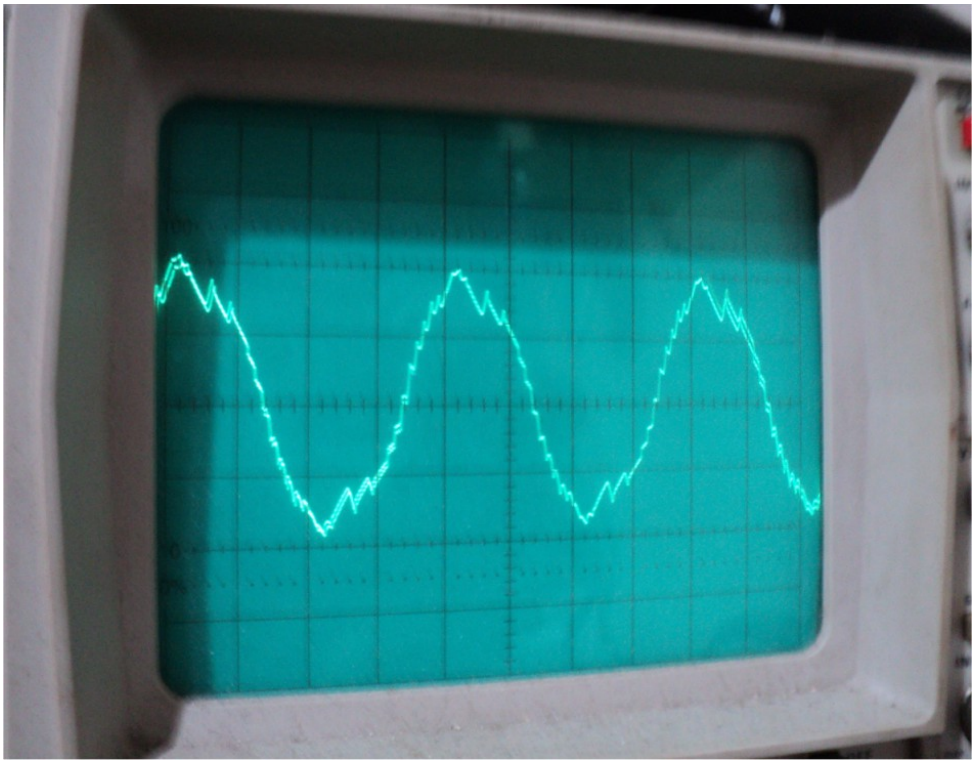
The "updated" SPWM waveform without filters (600 Hz driving)



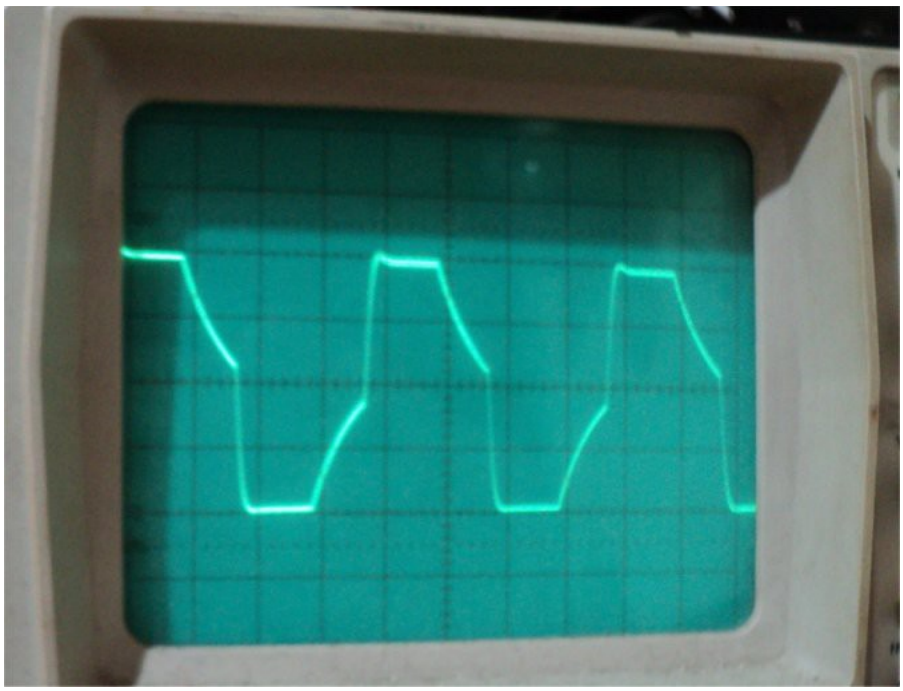
The SPWM waveform with 10μF output filter (600Hz driving)



The SPWM waveform with 10μF output filter (1 kHz driving)



“Heavy filtered” and attenuated (with L=4mH, C=10μF) for 600Hz driving
(RMS value of the above is 195V AC)



The Modified Square Wave mode (MSW) when “heavy loaded” (70% Load)
The above refers to D=60% with the 10μF output filter

Overall the project can be characterized as success (at least for me so far)... The output is holding to the predefined values and the switching of tables when changing loads or if voltage drops/rises outside the defined window was perfect. One point that could be better was, if the transformer ratio was not that small and had a higher ratio transformer (2x6V/220V instead of 2x9V/220V). That would have better results and allow higher frequency driving - but it was not available, so I had to work with the current setup...

The firmware of the MCU was programmed in Assembly. The final assembled file is 616 words (occupying only 30% of the mcu flash memory – which has 2048 bytes), so there is plenty of room for any future expansion or update...

One may ask...Why ATtiny25 ? Well if you want to go to the corner of your street, then you don't go with your car, but you go on foot instead ! Since ATtiny25 can do the job just fine, there is no really need to use an ATMega with 100 pins, to use just 3 ! Maybe if you program in C or Basic etc the alternatives could be ATtiny45 or ATtiny85 (same mcu with larger memories), but really there is no need to select a so much bigger microcontroller than the one that can do the job fine. That's why they have so many models, to choose the one for the job...

Overall it worked as expected and I'm more than pleased with the results... More to come if the free time is found somewhere... Up to this point, thanks for baring with me and reading so far... Any comments or suggestions would be very much appreciated... Any donations via paypal to nikos@tng.gr would be very much appreciated also... Comments or questions I would gladly answer if the answer is not already in this document (otherwise I will use the well-known RTFM !!!)

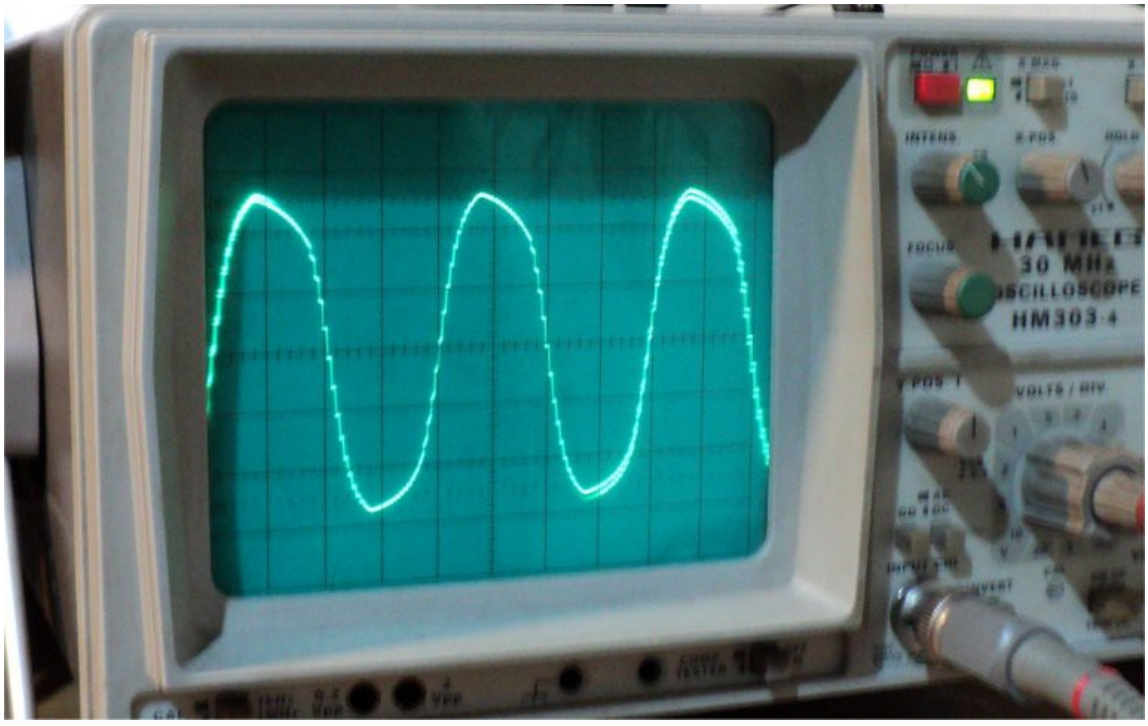
Until the next time be well... See ya !

Addendum #1

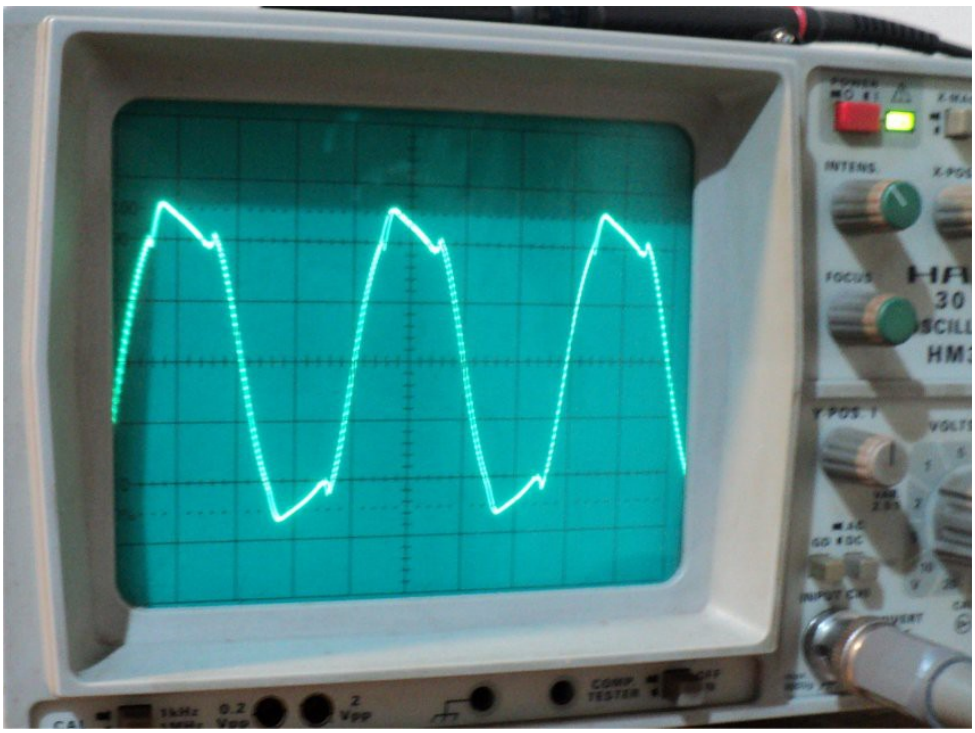
October 2019 Updates – Firmware Revisions 4 & 5 – Change of Email

Even though I had no reason of torturing myself, I decided to continue playing with this project for a while... In order to be a little more “satisfied” with the results, I decided to raise the MCU clock frequency to 8 MHz, in order to be able to use a driving scheme higher than 2 kHz... Indeed with 8MHz MCU clock, was easy to use 8 kHz SPWM signal. Three tables created for 3kHz, 5kHz, 8kHz SPWM driving.

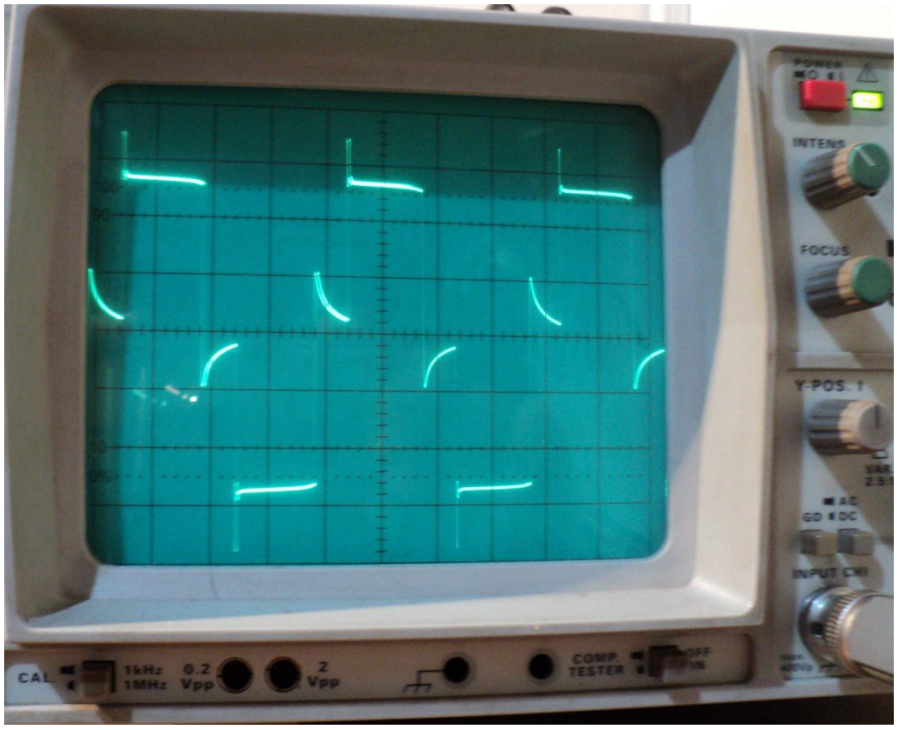
Note! Firmware Revision 3 wasn't ever presented in this document, as it was the same as V1 (before any updates mentioned in this document), with only MSW output waveform, but with the automatic control enabled as used in firmware V2 (instead of using the user-defined point) for 225 – 230V AC output (having 11 tables defined, from 40% MSW to 90% MSW in increments of 5%) and it is currently the working firmware of this power inverter. Since I've decided to increase the MCU clock frequency, two more versions produced (V4 for SPWM signal and V5 for MSW signal), since all loads that I mostly work with this inverter, are not very aware of the kind of waveform [a laptop (~ 80 Watt) or low power lights (~20 Watt), or small fan (~ 30 Watt) or a small computer (110 Watt) that I use in my lab]. Frankly because I mainly use those loads, the current firmware in this inverter is V5 (with Modified Square Wave output waveform and automatic output voltage regulation), the V4 for SPWM mainly constructed for “playing”...



Output voltage waveform for V4(5kHz SPWM) with 10μF output filter (100Watt Load)
(some artifacts shown in the waveform is from my “shaking hand”)



Output voltage waveform for V4(8kHz SPWM) with 10μF output filter (100Watt Load)
(some artifacts shown is also from my “shaking hand”)



Output voltage waveform for V5 (MSW) with 100Watt Load
This is the current working version in the inverter
The above is for 65% MSW driving

Also in this version, I changed my conduct email address for the reasons described in previous projects. For conducting please use: nikos@tng.gr

The package contain 2 firmware files, V4 and V5 and this document. I think that this concludes all possible information and updates that this project may ever have...

Until the next time be well and take care... See ya !