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Designing a Real Time Redactor for Power Saving Utilization

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***Abstract*—Nowadays high importance is given to the development of green technologies which are designed with an emphasis on low energy consumption. Due to the financial crisis the need for such green technologies and devices is more important ever before. All home electric appliances like refrigerators, deep-freezes, washing machines, pumps, etc. produce waste current component, which can be stabilized. This technique can decrease electricity consumption from 10 to 30% - different depending on countries. Current modern devices for adjustment of power of target electrical appliances need a very fine measurement of an input voltage and current. In such cases remote monitoring of mentioned values can be a suitable solution. However, this solution contains some issues such as the need for pre-processing in remote sensor, or wireless transfer to central monitoring device, which need to be solved. Also the powering of such remote device is strictly limited. Sensor needs to be powered only by energy from the current sensor which results in the need for application of modern power source solutions. All of these findings result in a development of miniaturized solution based on 32b microcontroller unit with wireless communication unit and independent powering circuit.**

***Index Terms*—Reactive power reduction, real time systems, measurement, industrial electronics.**

I. INTRODUCTION

If there is the need for power device, with working current of about 30 *Amp*, the common solution does not seem very realistic. The price of these devices is too high [1]–[3]. Isolation transformer which was intended to deliver more than 30 *Amp* is very heavy and huge in dimensions. Autotransformer is a good alternative, but the price also remains high. AC/AC switching power converter is considerably smaller, but its price is more than 3 times greater. Also, switching frequency in order of tenths of *kHz* is useless when powering standard AC devices, such as street lights, electrical engines and others. We have to develop a solution for obtaining electronically lower input RMS (Root Mean Square) voltage, while maintaining low price and dimensions. The basic principle is to use semiconductor switching device and proper driving circuit, which can achieve required results. In the later text we will call that device as 'reductor'. The main purpose of these devices is the reduction of output power which will lead to energy savings.

Our task was to design the device, which can easily lower input AC RMS voltage, while high current passes through it, without using isolation or autotransformer. The overall dimensions have to remain small as well as the weight does. The output voltage should be easily adjustable using any standard interface (UART, RJ-485, USB). Basically we had two options. The first was to build an AC/DC/AC converter, mostly known as frequency converter. This option was refused, because of lower overall efficiency and relatively high complexity. Also the switching semiconductors are relatively expensive and are sensitive to excess current and excess voltage. The second option was to develop the device, which is founded on a triac basis.

The operation using triac is very widespread. These devices are mostly used as speed regulation in drills [4]. Principle is the same, but overall design is somewhat different. Drilling speed regulation is designed to drive current machine. The attachment of another machine can harm the target device, or overheat and damage driver itself. On the other hand, currents over 30 *Amp* are not too widespread in drills, because of the overall size (12 *kW* drill is fairly heavy).

In present day, most solutions are founded on an autotransformer basis. The transformer is inserted into the main power line where it lowers the voltage to a required level. The most frequent mounting is presented as shown in Fig. 1.

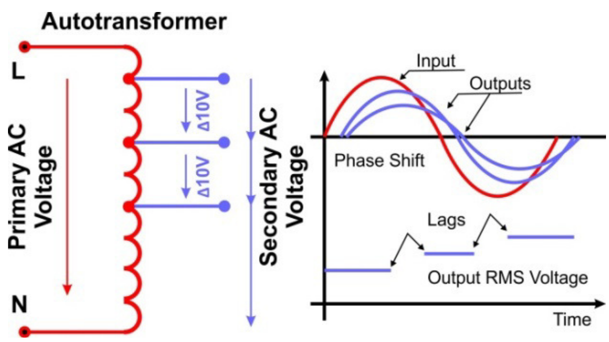

Fig. 1. Autotransformer function principle.

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Input voltage is lowered to the demand level by inserting the primary/secondary winding to the power path. One advantage of such setup is that output voltage progresses in the same way as input voltage. The current is significantly shifted over the voltage, but essentially it is not a problem. This shift is caused by inductance of the transformer. It can be compensated, but that is another issue. Autotransformer is significantly smaller than standard isolation transformer. Its secondary voltage is not separate from primary voltage. This feature causes that all the power does not pass through the transformer core which is the reason why it can be significantly smaller. High number of cases is solved by this principle. However, there are also disadvantages. Secondary voltage cannot be adjusted easily. There are step changes which need to be accounted for. Secondary winding has limited number of turnings. Usually, output voltage changes are in order of tens of volts and have no continuous running, but discrete. During every change, the output voltage disengages for a while and can cause visible flicking of the light or perceivable kick on the motor and others.

II. Driving on the Triac Basis

Triac unlike thyristor, it can conduct current in both directions.

Triac drivers are relatively simple. There are a threshold voltage resistor divider, a snubber network and a triac.

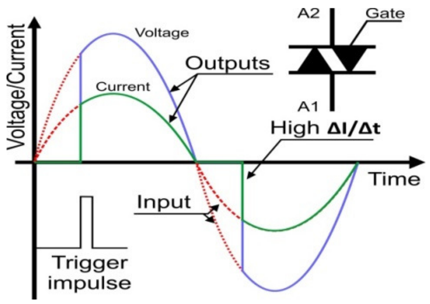

Fig. 2. Triac switching scheme principle.

Triac has to be activated by a single pulse for one half-period to the gate electrode. Then the passing current through the triac is held in a conduction state. One main disadvantage of the triac in comparison to the standard bipolar or unipolar switching components is that it cannot be switched off. Triac closes itself when passing current disappears. Then, it remains in a closed state until next trigger impulse is generated. In principle, we are cutting off a part of the sine wave. Therefore, the output running voltage is not clearly continuous, but partly discrete. The main switching waveform can be seen in Fig. 2. As we can see, maximum and minimum voltage levels are preserved. One value which will change is RMS voltage. RMS value is expressed by formula (1). If we are passing into the digital area RMS expression will change to (2), where n is the number of samples and *u(i)* is the actual voltage value:

$$Urms = \sqrt{\frac{1}{T}\int_{t0}^{t0+T} u^2\,(t)\,dt}, \qquad (1)$$

$$U_{RMS\ DISCRETE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} u_i^2}. \qquad (2)$$

Another problematic issue is the $\Delta I/\Delta t$ transition. The value of about 100 *A/μs* is very high and causes unwanted disturbances in higher frequencies. This is very important and the issue needs to be solved, because any disturbance may results in a failure of the devices in power line path.

III. Practical Solution

Two variants of redactors were established within the solution. One was based on an analogue principle and the other on the digital basis. The first redactor had one major disadvantage. It was not able to control output voltage continuously [5], [6]. There were resistor networks with DIP switch which controls output voltage level [7]. This solution is perfect for one concrete device. It is relatively simple and cheap, but it cannot accommodate for output or input changes. PCB of this design is presented on Fig. 3.

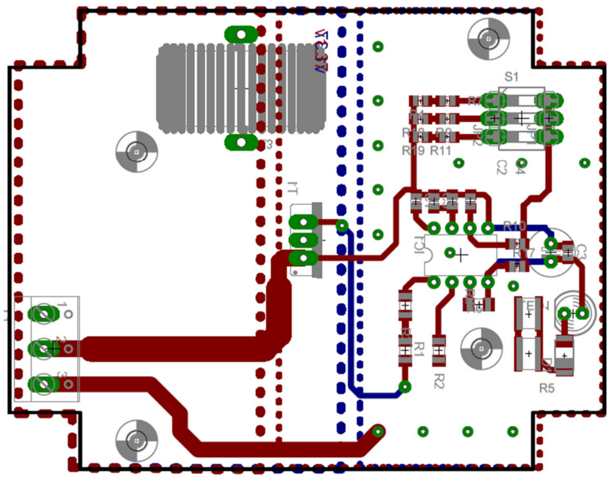

Fig. 3. Analog driver based reductor.

DIP switch S1 on the right top corner serves as a voltage setup. IC_1 circuit is a heart of the device. It is a special custom IC which is intended to drive power triac (T_1). It has a soft start function which ensures a proper start of the connected device. Another useful feature is circuit which is responsible for proper triggering of the triac. If the triac is not able to sustain open state, this device will try to trigger it again, until the conduction mode is achieved. But this reductor was only a temporary solution.

IV. MCU based Triac Driver

Analogue based triac drivers cannot react quickly enough to changes which are common in real world. Changes in load character, load amount, input voltage level and reactive power present real issues [1]–[3]. Especially reactive power is relatively dangerous, because it can cause triac to remain in a conduction state due to a phase shift of passing current. In terms of MCU (micro controller unit) in our case measures, among others, input and output voltage. The main task is to stabilize output voltage in demand level. Therefore, if we have output voltage value, we can adjust trigger pulse to be precise at a specific time which leads to the right RMS value. Having output voltage stabilized has one main advantage. If we are driving street lights voltage drop under safe level will lead to further lamps shutting down. It is obvious that right timing is critical. MCU is monitoring input voltage and current and their crossing through zero level. This is an important moment, because its value is proportional to the passing reactive current. Also the triggering impulse is derived from this precise time. The circuit which is responsible for the recognition of this time is very simple. It is a common comparator which is continuously comparing passing current with the ground signal. If the current is negative, comparator's output is logically 0. As soon as the current rises above the zero (ground) level, comparator turns over and its output is logically 1. The same comparator is on the voltage side and the time between both transitions is proportional to the phase shift between voltage and current (reactive current). The matching resistor network aimed at measuring high AC voltage and current is shown in Fig. 4.

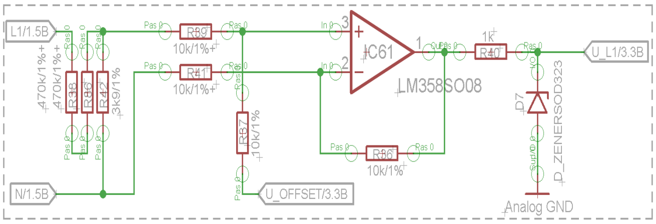

Fig. 4. Matching resistor network necessary when measuring high AC voltage and current.

There are 3 resistors on the input side. Two of them have the same resistance values. Standard SMD resistor has voltage of about 200 *V*. If the voltage is higher, disruptive breakdown will occur and high voltage will appear on the low voltage circuits' parts. Then the resistor divider lowers input voltage 241 times, so the output voltage applied to MCU A/D inputs becomes about ±1 *V*. The negative part has to be overridden, because of MCU inputs. The negative voltage can harm that device, even if it is as small as 1 *V*. As we can see in Fig. 4, operational amplifier is connected as differential amplifier. Offset voltage is applied to the non-inverting input, so the output signal is increased to about the level of the offset voltage (U_OFFSET). As a result, we have the same voltage running as is present on the power line, but proportionally lower and shifted upwards.

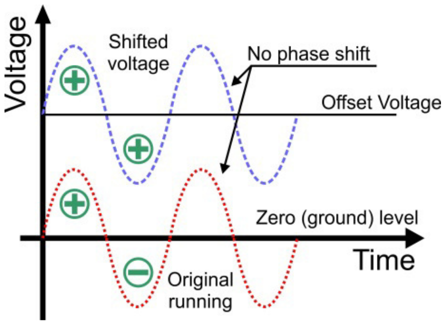

Fig. 5. Shifting upwards input voltage to avoid negative voltage to be present on MCU inputs.

This is very important and its principle is presented in Fig. 5.

Current measuring is in principle the same. The most efficient way of measuring passing current is to use the current transformer. It is a widely used, cheap component with a very simple principle. The passing AC current forms alternating magnetic field which induces voltage in the secondary winding. This is a contactless measuring form, because the wire acts as a primary winding and magnetic lines are closed within the sensors winding (Fig. 6).

The same voltage pattern, as is in the passing current, is presented in the probes terminal (only proportionally smaller). Of course, there is a small shift between real current and probes recorded current, but if proper components are used, this error is smaller than 1%. This wave is also differently scanned and shifted upwards to sustain the ability to measure both half waves.

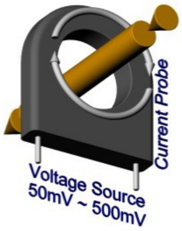

Fig. 6. Current probe shape and features.

Now, this running can be converted to the digital areas. Each period is sampled with 20.000 *Hz* sampling rate. It is equal to 400 sampled points per period. These data are stored in external SRAM memory, because MCU itself does not have enough memory capacity. We tried to increase the number of sampled points, but the results remain almost the same. Therefore, it appears to be sufficient number.

V. TRIAC DRIVING

It's not easy to drive triac since there is a high voltage on its gate electrode. MCU and support circuits are supplied from low voltage power source (5 *V*). Therefore the question which arises is how to switch ON triac by low voltage source. Essentially we only have one possibility. Using an opto-coupler is an elegant way of making this possible. Opto-coupler has the LED on its one side, and opto triac on the other. Activated LED turned the switch opto triac ON. This principle is shown in Fig. 7.

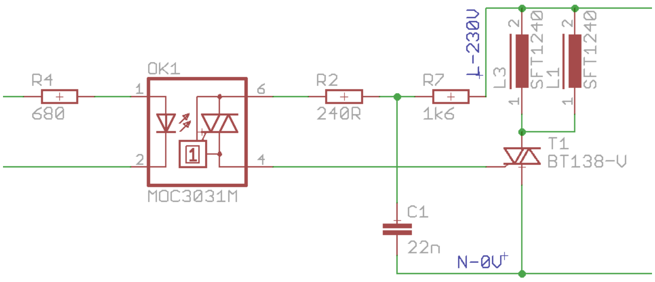

Fig. 7. Using low voltage Opto-Triac to drive high voltage, power Triac.

This type of driving has one more advantage. We can control unwanted $\Delta I/\Delta t$ transition by setting R7 and C1 values. If the opto triac starts to conduct, current from the input (L-230 *V*) will pass through the R_7 and R_2 resistor to the T_1 gate. This will cause the main triac to turn ON. Triggering impulse has to deliver at least 50mA. Once the triac is opened, the passing current will keep it open.

Snubber network created by R_7 and C_1 will limit initial current slope to a tolerable level. In addition, it can limit switching disturbance by shortening high frequency transients. In case that we do not use snubber network, the output will become such as in the Fig. 8.

$\Delta I/\Delta t$ transition can be partly controlled by snubber network, but it only servers as a supplementary item. The main $\Delta I/\Delta t$ limiter existence is caused by series inductor L_1

and L_3. They are parallelly connected to increase current rating.

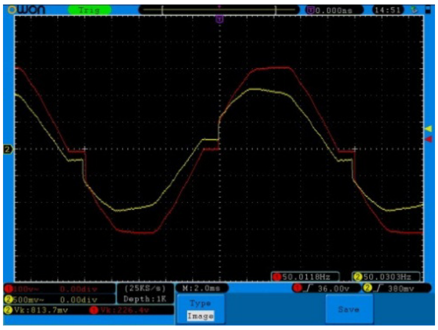

Fig. 8. High Δ*I*/Δ*t* transient causing high RF disturbance.

If the high current slope appears, inductance will counteract and lower the slope to a convenience level. There is an important matter to consider. The inductor core material has to be chosen carefully, because for example ferrite core cannot handle low frequency current and then acts as an ordinary serial resistance. This results in no Δ*I*/Δ*t* reduction being present. The standard iron core inductors with proper inductance should be used when working with standard 50/60 *Hz* current.

By conducting tests we proved that with the slope limiting inductor, the output is much neater (meaning in terms of harmonic frequency) than in the case without it. In Fig. 9 a clearly trimmed voltage is presented as running on resistive load.

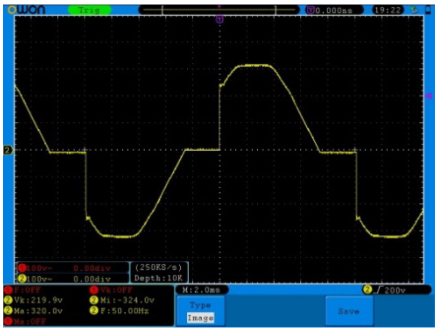

Fig. 9. Voltage running on resistive load with pure trimmed part.

The original sine voltage is trimmed without any slope limiting. The rising edge is very steep and its level depends on the used triac. This type of switching is the most efficient, because the switching triac is in full conduction mode, or is closed. On the other hand, this running causes high electromagnetic interferences which can be seen in Fig. 10.

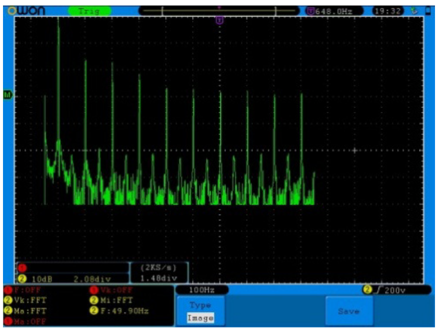

Fig. 10. Simple FFT analysis on the load side without slope limiting.

It is obvious that electromagnetic interference is much lower when using large inductor (26mH) as an attenuating element. Grid resolution is the same as in the previous picture. The harmony with lower peaks almost completely disappears and the characteristics are derived from 100Hz basis. The output voltage running is presented in Fig. 12.

The highest peak is on 50Hz and then the higher and lower level peaks alternate. This FFT analysis is done in the used oscilloscope and is more or less informative, but for this purpose it is enough. The grid resolution is 50Hz; the relative amplitude on the Y axis is in dB. When using the slope limiting (ΔI/Δt) inductor, electromagnetic interference significantly falls back, as it can be seen in Fig. 11.

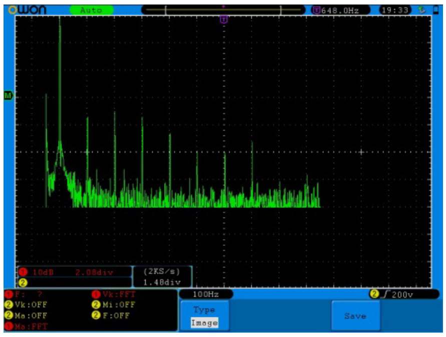

Fig. 11. When using ΔI/Δt limiting component, the interference is significantly lower.

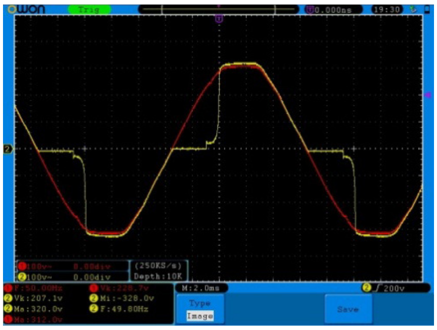

Fig. 12. Voltage running on resistive load with connected damping inductor (yellow curve) and original input sinusoidal voltage (red curve).

Comparing Fig. 9 and Fig. 12, the edges are rounded and primary rising edge is not as steep. The switching triac is driven in the same way as previously and all damping work is done by the inductor. This wiring diagram is mandatory to avoid excess EMI which is an unwanted effect in electrical circuits. This is only the first stage; the second stage will be presented further in the text.

As we mentioned above, the high current slope levels are causing high disturbance in the main power line. In order to precede this state, special care must be devoted to PCB design. Power traces must be as short as possible and ground signal has to be spilled out on the PCB. PCB design is shown in Fig. 13. This device must work in cooperation with passive filter to avoid passing of the disturbance back into the power line path. Without this filter the developed device cannot be connected to the customer line, because of the EMC (Electro Magnetic Compatibility) law violation.

EMC filter values can be calculated, but the final inductor’s and capacitor’s values must be trimmed on the basis of practical tests. The Electrical scheme of this filter is standard (Fig. 14).

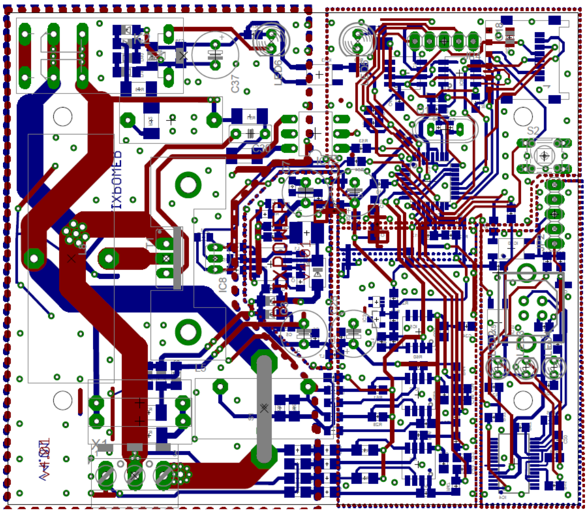

Fig. 13. Reductors PCB design. Power traces has to be as short as possible.

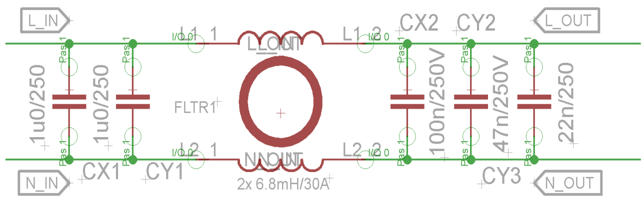

Fig. 14. Passive filter to satisfy EMC.

This special device is called the suppression choke. This filter must reduce high frequency disturbance and that is why it must be inserted between interconnecting wires and useful and disturbing current must pass through it. For low frequencies the reactance of inductor is very low and essentially has no effect on passing current. On the contrary, disturbing, high frequency signal is suppressed by high reactance of this inductor. Suppression function of the inductor is especially important in circuits with low impedance, where the impedance of the source and the load are much lower than the reactance of the inductor. Suppression chokes are mostly wind on ferrite or iron chokes, mostly toroidal shapes. On Fig. 14 the choke with unusual winding is presented. There are two windings on the same choke. The wires are connected as we can see in the figure. Therefore, the magnetic flow generated by working current is compensated. The core is then saturated only by unsymmetrical currents. This leads to a suppression of unsymmetrical disturbances which are generated from triac switching.

Apart from the inductors, capacitors are also present. For low frequencies the capacitor acts as a high reactance, so the impact to the power line is insignificant. On the contrary high frequency noise is suppressed, because of low reactance of the capacitor. A good filter is essential in order to avoid disturbance which can harm any connected device on the power line and in addition EMC might not be met.

VI. ADDITIONAL FEATURES OF THE REDACTOR

The reductor device is primarily intended for smaller RMS voltage in order to lower output power (meaning energy savings). If we solve problems with triac switching and EMC issues, we can focus on the other problems such as low switching current, excessive current state, smooth transients, communications' protocols, real time clock (RTC), data recording and others [8].

Low switching current can be problematic. If we have no sufficient current, triac cannot feed itself and turn itself to OFF state after successful triggering to conduction state. This state can cause an unwanted disturbance which infests power line. In order to successfully avoid this state, the intelligent bypass is present. If the device detects current under the threshold level, a relay is switched on (or high current clamper). This relay bypasses the triac which results in an effective solution. A similar state can occur when excessive current is detected. Excessive current can harm triac and destroy the redactor. Therefore, if the redactor detects the excessive current state, relay will become involved again.

If the power saving is recognised, RMS voltage level will be lowered to about 20 *V* at least. This could cause an unwanted power step which is visible as a little light flick (street light or something alike). This light flick is a common phenomenon when using standard redactors from most vendors. If MCU is present as a control unit, we can program its behaviour to gradually reduce RMS voltage level. This is done in small steps with variable intervals between them. MCU has a 16bit timer which theoretically provides steps of about 65.000 volts. In terms of voltage, one step equals to 3.5 *mV*. In comparison to autotransformer, it must have 65 thousand taps. Practically, it has no meaning, therefore about 2 thousand steps were chosen. This is enough for smooth transition from full power state to reduction state without noticing. The redactor block diagram is presented in Fig. 15.

In such way we can setup the device and precede all unwanted states. It is necessary to know all the details about the power line, voltage and current levels, reactive power amount, switching details, load character and undeniably also time. If a problem arises, without historical data, we can only guess what has happened. For that reason RTC (Real Time Clock) [9] and data recording function is present. RTC has its own backup battery, so it can function over the period of time without AC line voltage. The measured data are periodically saved on a microSD card with the current time stamp. Time spacing between records is set to 3s. It is enough to evaluate the incurred problem.

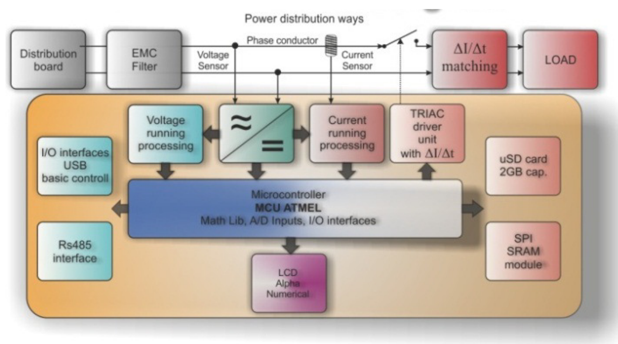

Fig. 15. Redactor block diagram [10].

Each time about 30 items is recorded, so 2GB card lasts for about 2 years. Then the oldest data are rewritten. The software interface is presented in Fig. 16.

The recorded quantities are presented on the left side. For example, RMS input and output voltage, average input voltage (to establish whether the load is non-symmetrical), RMS current, its maximum and minimum values, frequency, effective power, reactive power, apparent power, current phase shift angle, temperature and many others. This software is intended for setting up and monitoring of the installed reductor. In addition, the input and output voltage and current running are observable.

Fig. 16. Control software demonstration.

The final product can be seen in Fig. 17 and Fig. 18. A large heat sink can be noticed there. It is very important, because the switching device dissipate a lot of heat. It is due to the voltage drop over the triac. It is about 1.6 *V* which leads to 48 *W* of heat (1.6 *V* time 30 *A*) which must be dissipated.

Fig. 17. Finished PCB with mounted parts. Current probe is in the top middle.

Fig. 18. Large heat sink is mandatory, because of heat dissipation of triac.

VII. CONCLUSIONS

The presented device is an alternative to robust and heavy transformer based energy savers (reducer) [11]. Unlike these, this device uses active semiconductor switching topology to reduce RMS voltage [12]. Smooth transitions of output voltage make it ideal to control any kind of lights. There is no noticeable change in comparison to normal state which is exactly what customers are looking for. Many other features create a complex unit which is suitable to analyse problems in the power line path [13]. Also the price is much lower than the competitor’s ($300).

The main contribution of this paper is the application of microcontroller unit into the device to control output RMS voltage. The basic task was to create a device which can modify the output voltage on the load, but does not have such disadvantages that do these devices on transformer basis. The main issue is the small voltage interruption, when switching between transformer taps. This causes unwanted dropout. The only possible option is a device based on semiconductor switches which is controlled by a microcontroller unit due to precise timing without any delays. Finally, the developed device can drive extension board with multipurpose focus which can add value to the device. All other information which needs to be obtained from the practice is presented in this paper.

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