Reduction of Reactive Power for Power Saving Utilization at Home Power Lines

Ondrej Krejcar and Robert Frischer
Department of Information Technologies, Faculty of Informatics and Management, University of Hradec Kralove, Rokitanskeho 62, Hradec Kralove, Czech Republic

Keywords: Reactive Power Reduction, Real Time Systems, Measurement, Industrial Electronics.

Abstract: In recognition of the ever increasing energy prices, reactive power compensation is getting more and more into the forefront. Climate protection and energy is one of the most discussed issues of current policy. Production of electrical energy from primary sources to its consumption occurs however in the process of losses. Although these total losses are obviously only a small portion of the current-dependent losses in electricity transmission, the final absolute value of those losses go to billions of kilowatt. Part of the current-dependent losses in networks raises inductive reactive power from the operation of common appliances. Many home electric appliances like refrigerators, deep-freezes, washing machines, washers, pumps, etc. produce vaste energy called reactive power, which can be reduced. This technique can lower electricity consumption (from 10 to 30% - different by countries). Current possibilities of devices for reduction of reactive power for home usage are only very limited with high price. Paper deal with a development of miniaturized solution based on 32b MCU (Micro Controller Unit) with wireless communication unit and independent powering circuit. We mentioned need of a very fine measurement of an input voltage and current as well as remote monitoring option.

1 INTRODUCTION

If there is a need to power device, with working current about 30Amp, a common solution now seems not very realistic. Price of these devices is very high. Isolation transformer which intended to deliver more than 30Amp is very heavy and huge in dimensions. Autotransformer is good alternative, but price also remains high. AC/AC switching power converter is dramatically smaller, but its price is more than 3 times greater. Also switching frequency in order of tenth kHz is useless, when powering standard AC devices, like street lights, electrical engines and so on. We have to develop a possibility to electronically lower input RMS voltage, while maintain low price and dimensions. The basic principle is to use semiconductor switching device and proper driving circuit, which can achieve demand results. In the further text we will call that device the reductor. Main and only purpose of these devices is in its ability to reduce output power, which will lead to the energy savings.

Our task was to design the device, which can simply lower input AC RMS voltage, while high current can pass through it, without using isolation, or autotransformer. Overal dimensions have to remain small as well as the weight. Output voltage should be smoothly adjustable through 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 switching semiconductors are relatively high on price and are susceptible to over current and over voltage conditions. The second option was to develop the device, which is based on triac basis.

Driving using triac is very widespread. Mostly are these devices used as speed regulation in drills. Principle is the same, but overall design is somewhere else. Drilling speed regulation is designed to drive current machine. Connecting another one can harm the target device, or overheat and damage driver itself. On the other hand, currents over 30Amp aren't too much widespread in drills, because of the overall size (12kW drill is fairly heavy).

In present day, most solutions are based on

Krejcar O. and Frischer R..
Reduction of Reactive Power for Power Saving Utilization at Home Power Lines.
DOI: 10.5220/0004582804770484
In *Proceedings of the 10th International Conference on Informatics in Control, Automation and Robotics* (ICINCO-2013), pages 477-484
ISBN: 978-989-8565-70-9

autotransformer basis. Into the main power line is putted the transformer, which lower input voltage to the demand level.

Input voltage is lowered on demand level by inserting the primary/secondary winding to the power path. One advantage is that output voltage has the same running as input voltage. There is significantly shifted current over the voltage, but essentially it isn't a problem. This shift is caused by inductance of the transformer. It can be compensated, but this is another issue. Autotransformer is significantly smaller than standard isolation transformer. Its secondary voltage isn't separate from primary voltage. This feature caused, that through the transformer core don't pass all the power, and that's why it can be significantly smaller. Overwhelming cases are solved by this principle. There are also disadvantages. Secondary voltage can't be adjusted smoothly. It has step changes. Secondary winding has limited number of turnings. Mostly output voltage changes are in order of tens of volts and haven't continuous running, but discrete. On every change, the output voltage disengages for the while and it can cause visible blinking of the light or perceivable kick on the motor and so on.

In recognition of the ever increasing energy prices, reactive power compensation is getting more and more into the forefront of. Climate protection and energy is one of the most discussed issues of current policy. Electricity, which is a form of energy with the highest credit rating, is in the centre of these discussions. During the production phase of electrical energy in power plants where it is burning a coal, oil and gas, a carbon dioxide (CO2) is primarily released in huge amounts, what negatively affects the climate. Production of electrical energy from primary sources to its consumption occurs however in the processes of losses. Although these total losses are obviously only a small portion of the current-dependent losses in electricity transmission, the final absolute value of those losses go to billions of kilowatt. Part of the current-dependent losses in networks arises inductive reactive power arising from the operation of common appliances. These losses can be avoided by offsetting.

2 PROBLEM DEFINITION

Electric components consume a power from the electric network (power line), which is generally the product of current and voltage. This performance is taken further in the appliance and converted into useful power, which is referred to as an active power P.

When electrical appliances, working on the induction principle, are connected to AC, (three-phase current), they take from the power line an extra power which is need to create a magnetic field which is then fed back into the power line.

This "useless" - reactive power Q and shuttling between the source (generator) and the appliance inside and outside (Fig. 1) and in addition to the active power P it burdens generators, transformers, transmission lines of High and Very High Voltage and electrical distribution system in Low Voltage power lines.

Appliance with no corrections of reactive power as can be seen on (Fig. 1), the supply is required to provide the total active and reactive power on demand of the load.

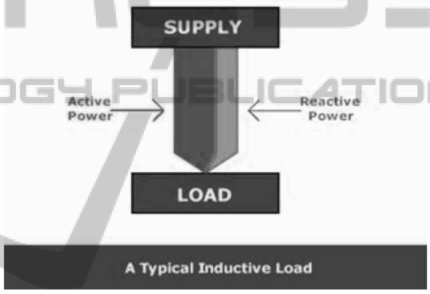

Figure 1: Appliance with no corrections of reactive power.

At the other side, when appliance is installed with a capacitor - electrically adjacent to a load, the supply is required only to provide the active power on demand. Only smaller proportion of the reactive power is needed on demand from source power line (Fig. 2).

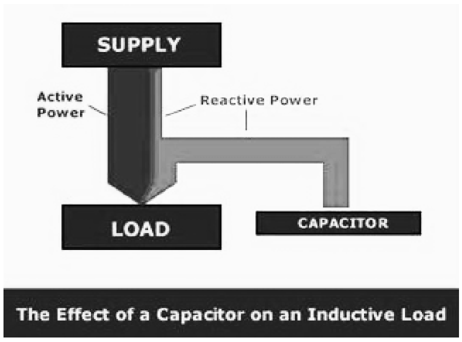

Figure 2: Appliance is installed with a capacitor.

The vector sum of active and reactive power is called apparent power and indicates a capital S. Appliances in energetic grids are usually inductive in nature. Reducing inductive reactive power can be achieved by parallel connection of capacitors for induction appliances. This makes returning reactive power, which was used to create a magnetic field, "stored" in the condenser and plies only between the capacitor and the induction appliance. Power capacitor has a capacitive and inductive directed against the performance of the appliance. Power factor when required, but incomplete compensation of inductive reactive power changes from the cos φ cos φ '(Fig. 3).

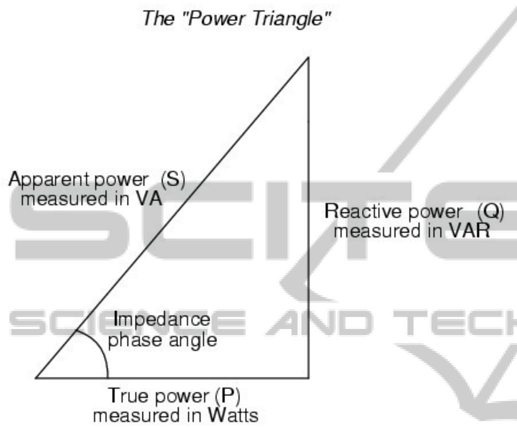

Figure 3: Reactive power introduction.

Problem of unstable running of electric power in home or small office electric power line as well as the low quality of electric power which can go up to 25 % in some cases led to the need of complex solution to reduce or fully compensate mentioned malfunctions.

Cases where is the extreme need of compensation are mainly in computer solutions area, where some specific applications need very precise and stabile voltage running (in other case the used technology can became broken or damaged).

All mentioned problems also grow up in home or small offices, where some common electrical appliances are widely used. As example it can be specify as refrigerators, freezers, home pumps, hair dryers, and other examples containing electrical engines (motors).

Mentioned problems grown up only in home or small office cases, because at a higher level power lines (mid-size and large size companies) a regulation from government need to be done every time (Corcorana et al., 2012). Large companies need to take care of quality of their power lines alone and the solutions are well known widely even in the markets.

Nowadays a power consumption still growing up due to the usage of many electrical appliances even in case the users bought energy save devices. (Yang, 2008), (Cohen, 2012).

Based on previous discussion a problem of home power lines can be defined as a need of:

- Overvoltage reduction;
- Decreasing phase shift;
- Increasing of appliances lifetime (up to 40%);
- Increasing of quality of power for power line;
- Decreasing of environmental sources consumption;
- Decreasing of electric power consumption by 25 %;
- Low cost solution – quick recovery of investment.

Following chapter will discuss existing solutions for partial or complete (if exists) solving of defined problems.

3 RELATED WORK

There are many existing solutions for reactive power shifting or reducing like one from (Rathika and Devaraj, 2010), where they developed a solution of fuzzy logic-controlled shunt active power filter which is capable to reduce the total harmonic distortion. Their simulation results show some level of effectiveness of proposed solution for harmonic reduction, not for power line quality nor the power save. This solution can be used to solve only particular solution.

Another authors (Gao and Peng, 2010) presents two methods to reduce the reactive power at converter topology level and control level respectively. Presented study has been performed to decrease the total reactive power for real tokamak to reduce the overvoltage and to avoid low-frequency resonant caused by the fast and large reactive power variation within 20ms. Solution of tokamak is quite far of home power line usage, but there are some interesting and usable techniques, which can be partially used. This is however not complex solution as requested.

Third research paper (Zhao et al., 2009) describe a wind farm which is made with doubly fed induction generators (DFIG) as the continuous reactive power source to support system voltage control due to the reactive power control capability of DFIG. The particle swarm optimization (PSO) is utilized to find wind farm optimal reactive power output for distribution system losses reduction and voltage profiles improvement. Finally, the three feeder distribution system is used as a test case to evaluate the algorithm. This solution is almost the best of each ones we found in research databases, but the cost of solution and complexity is too high for home purposes.

The last one solution we found as a literature with topics close to our research (Rao and Vaisakh 2006) deal with network sensitivity between load voltages and source voltages, what is used as the basis to evaluate optimal real power generation allocation for loss and marginal cost reduction. Authors also present a method for optimum allocation of reactive power in day-to-day operation of power system for loss reduction. The described technique try to utilize fully the reactive power sources in the system to improve the voltage profile and to minimize the real power losses besides meeting the optimal real power generation levels. Although this paper describe very interesting solution, there are a lot of missed technical details without them it is not possible to run the system as correctly as it is requested.

Due to the absence of research output with full and complete low cost solution, we will describe several methods in details as well as with all technical knowledge, what is needed to develop requested solution.

4 CURRENT STATE OF THE ART

Triac are in principle two antiparallel connection of thyristors. Unlike the thyristor, it can conduct current in both directions.

Triac drivers are relatively easy. There is a threshold voltage resistor divider, snubber network and triac. Triac has to be activated by single pulse (For one half-period) to the gate electrode. Then the passing current through the triac hold it in the conduction state. One main disadvantage of the triac against standard bipolar or unipolar switching components is that it can't be switched off. Triac close itself when passing current disappears. Then remain in closed state until next trigger impulse is generated. In the principle, we are cutting off part of the sine wave. So the output running voltage isn't clearly continuous but partly discrete. Maximum and minimum voltage levels are preserved. One thing which will change is value of RMS voltage.

Another annoying thing is $\Delta I/\Delta t$ transition. Value about 100A/µs is very high a causing unwanted disturbances on higher frequencies. This is maybe most important thing, has to be solved, because any disturbance may results in failure of the devices in power line path.

4.1 Analog Triac Driving

Within the frame of solution were made two variants of reductors. One was based on analog principle while the other on the digital basis. The first one has one major disadvantage. It was not able to control output voltage continuously. There were resistor networks with DIP switch, which control output voltage level. This solution is perfect to one concrete device. It is relatively simple and cheap, but it can't accommodate to output or input changes. It has a soft start function, which ensures a proper start of the connected device. Another useful feature is circuit, which is responsible to proper triggering of the triac. If the triac is not able to sustain in open state, this device is trying to trigger it again, until the conduction mode is achieved. But this reductor was only a temporary solution.

4.2 MCU based Triac Driver

Analog based triac drivers can't react quickly enough to changes, which are common in real world. Changes in load character, load amount, input voltage level or reactive power present are real issues. Especially reactive power is relatively dangerous, because it can cause, that triac will remain in conduction state, because of phase shift of passing current. If we are using MCU (micro controller unit), we can span every possible occasion, we can imagine and make an algorithm to precede it. In our case, MCU is measuring, among others, input and output voltage. Main task is to stabilize output voltage on demand level. So if we have output voltage value, we can adjust trigger pulse to be precisely in specific time which leads to 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 will shut 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 passing reactive current. Also triggering impulse is derived from this precise time. Circuit which is responsible for recognition this time is very simple. It is common comparator, which is continuously comparing passing current with the ground signal. If the current is negative, comparators output is logical 0. As soon as the current rise above the zero (ground) level, comparator turn over and its output is logical 1. Same comparator is on the voltage side and the time between both transitions is proportional to phase shift between voltage and current (reactive current). Matching resistor network to measure high AC voltage and current is shown in (Fig. 4).

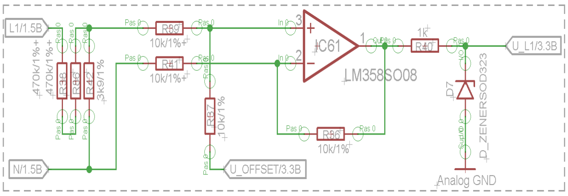

Figure 4: Matching resistor network necessary when measuring high AC voltage or current.

There are 3 resistors on input side. Two of them has the same resistance value. They are two, because of high voltage stress applied on them. Standard SMD resistor has voltage rating about 200V. If the voltage is higher, disruptive breakdown will occur and high voltage appears on low voltage circuits parts. Resistor divider then lower input voltage 241 times, so the output voltage applied to MCU A/D inputs is about ±1V. Negative part has to be override, because of MCU inputs. Negative voltage can harm that device, even if is as small as 1V (Fig. 4). Operational amplifier is connected as differential amplifier. Offset voltage is applied on non inverting input, so the output signal is shifted up just about 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 up.

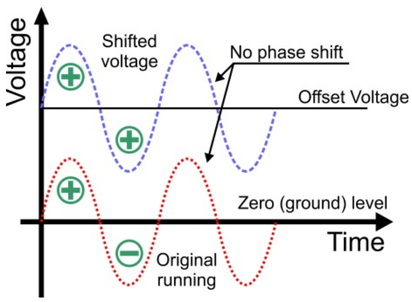

Figure 5: Shifting up input voltage to avoid negative voltage to be present on MCU inputs.

This is very important thing and its principle is presented on (Fig. 5).

Current measuring is in principle the same. The most efficient way how to measure passing current is to use current transformer. It is a widely used, cheap component with a very simple principle. Passing of AC current forms alternating magnetic field, which induce a voltage on the secondary winding. This is a contactless measuring form, because the wire acts as primary winding and magnetic lines are closing through the sensors winding.

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

Now can be these running converted to digital area. 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 has not enough memory capacity. We tried to increase number of sampled points, but results remain almost the same. So it appears to be sufficient number.

5 REDUCTOR DESIGN

It's not easy to drive triac. There is a high voltage on its gate electrode. MCU and support circuits are supplied from low voltage power source (5V). The question is, how to switch ON triac by low voltage source. Essentially we have got only one possibility. Using an opto-coupler is an elegant way how to make this possible. Opto-coupler has the LED on its one side, and opto triac on the other. Activated LED caused switch opto triac ON. This principle is on (Fig. 7).

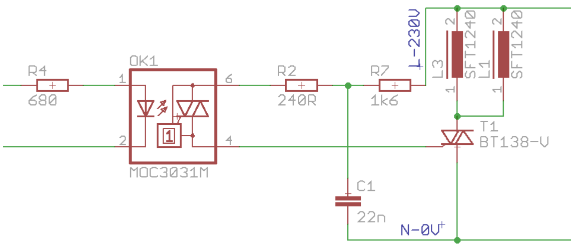

Figure 7: Using low voltage Opto-Triac to drive high voltage, power Triac.

This type of driving has one more advantage. We can control unwanted ΔI/Δt transition by setting R7 and C1 values. If the opto triac starts to conduct, current from input (L-230V) passing through the R7 and R2 resistor to the T1 gate. It will cause to switch main triac ON. Triggering impulse has to deliver at least 50mA. Once the triac is opened, passing current will keep it open.

Snubber network created by R7 and C1 will limit initial current slope to tolerable level. In addition it can limit switching disturbance by shorting high frequency transients. In case, that we wouldn't use snubber network, the output would be like in the (Fig. 8).

Figure 8: High ΔI/Δt transient causing high RF disturbance.

ΔI/Δt transition can be partly controlled by snubber network, but it servers only as supplementary item. Main ΔI/Δt limiter is caused by series inductor L1 and L3. They are connected at parallel, to increase current rating. If the hi current slope appear, inductance will counteract and slowdown the slope to convenience level. There is a one important thing. Inductor core material has to be chose carefully, because for example ferrite core can't handle low frequency current and then acts like ordinary serial resistance. That led into that no ΔI/Δt reduction is present. There should be use standard iron core inductors with proper inductance if we are working with standard 50/60Hz current.

As we mentioned above high current slope levels are causing high disturbance into the main power line. To precede this state, special care must be devote 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. 9). This device must work in cooperation with passive filter to avoid passing disturbance back into the power line path. Without this filter it can't be connected to the customer line, because of EMC (Electro Magnetic Compatibility) law violating.

EMC filter can be calculated, but final inductor and capacitor values must be trimmed on the basis of practical tests. Electrical scheme of this filter is common (Fig. 10).

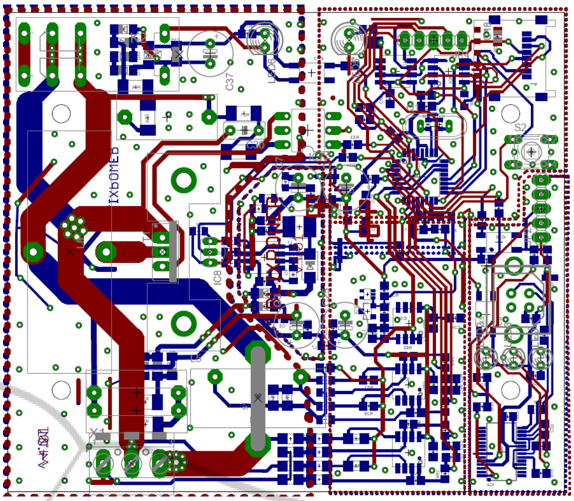

Figure 9: Reductors PCB design. Power traces has to be as short as possible.

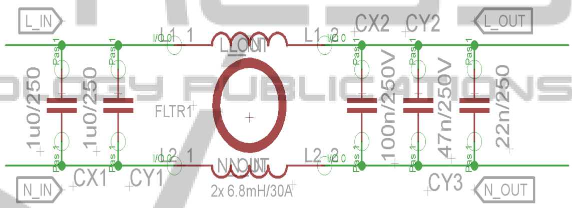

Figure 10: Passive filter to satisfy EMC.

This special device is called suppression choke. This filter must reduce high frequency disturbance and that's why must be inserted between interconnecting wires and useful and disturbing current must pass through it. For low frequencies is reactance of inductor very low and essentially has no affect to passing current. On the contrary, disturbing, high frequency signal is suppressed by high reactance of the inductor. Suppression function of the inductor is especially expressive in circuits with low impedance, where impedance of the source and load are much lower, than reactance of the inductor. Suppression chokes are mostly wind on ferrite or iron chokes, mostly toroidal shapes. On (Fig. 10) is presented choke with unusual winding. There are two windings on the same choke. Wires are connected as we can see on the figure. So the magnetic flow generated by working current is compensated. Core is than saturated only by unsymmetrical currents. That led to suppress unsymmetrical disturbances which are generated from triac switching.

Except inductors, there are present also capacitors. For low frequencies the capacitor acts as 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. Good filter is essential. Without it, disturbance can harm any connected device on the power line and in addition EMC doesn't meet.

6 ADDITIONAL FEATURES OF REDUCTOR

The reductor device is primary intended to lower RMS voltage in order to lower output power (it means energy savings). If we pass away problems with triac switching and EMC issues, we can focus to the other problems like low switching current issue, over current state, smooth transients, communications protocols, real time clock (RTC), data recording and so on (Dodiu et al., 2010).

Low switching current can be problematic. If we have no sufficient current, triac after successful triggering to conduction state can't feed itself and turn to off state. This state can cause unwanted disturbance, which infest power line. 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 will bypass the triac and everything goes well. Similar state can occur when over current is detected. Over current can harm triac and destroy the reductor. So if the reductor detect over current state, relay again involve.

If the power saving should be sensible, RMS voltage level has to be lowered about 20V at least. This could cause unwanted power step, which is visible as a little blink (street light or something like). This blink is common phenomenon when using standard reductors from most vendors. If we have MCU as a control unit, we can program its behavior to reduce RMS voltage level gradually, in small steps, with variable time between them. MCU has 16bit timer which give us theoretically about 65.000 voltage steps, in voltage expression one steps equal to 3.5mV. In comparison to autotransformer it has to have 65 thousand taps. Practically it has no meaning, so about 2 thousand steps were chosen. It is enough to smooth transition from full power state to reduction state without noticing. Reductor block diagram is presented on (Fig. 11).

So as we can setup the device and precede all unwanted states, we need to know all details about power line, voltage and current levels, reactive power amount, switching details, load character and of course also time. If problem once originate, without history data we can only guess, what happened. For that reason RTC (Real Time Clock) and data recording function is present. RTC has its own backup battery, so it can function over the period without AC line voltage. Measured data are periodically saved on microSD card with the current time stamp. Time spacing between records are set to 3s. It is enough to evaluate incurred problem.

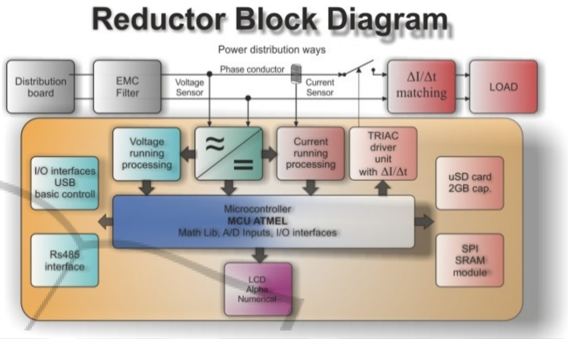

Figure 11: Reductor block diagram (Krejcar and frischer, 2012).

7 CONCLUSIONS

Presented device is an alternative to robust and heavy transformer based energy savers (reducer). Unlike them, this device uses active semiconductor switching topology to reduce RMS voltage. Smooth transitions of output voltage make it ideal to drive any kind of lights. Any change isn't noticeable and that's the thing that customer want. Many other features make a complex unit, which is suitable to analyze problems in power line path. Also price is much lower than in competitor's ($300).

ACKNOWLEDGEMENTS

This research was funded by a grant (Smart Solutions in Ubiquitous Computing Network Environments) from the Grant Agency of Excellence, University of Hradec Kralove, Faculty of Informatics and Management, Czech Republic and by a grant (SP/2013/03 - SmartHomePoint Solutions for Ubiquitous Computing Environments) from University of Hradec Kralove. This research was performed in cooperation with the Cautum Company (http://cautum.cz/).

REFERENCES

Alturki, Y. A., Lo, K. L., 2010. Real and reactive power loss allocation in pool-based electricity markets, *International Journal of Electical Power & Energy Systems*.Elsevier: England, Vol. 32, Issue 4, pp. 262–270.

Augustynek, M.; Penhaker, M. Non invasive measurement and visualizations of blood pressure. Electron. Electr. Eng. 2011, 116, 55–58.

Brida P., Machaj J., Duha J., 2010. A Novel Optimizing Algorithm for DV based Positioning Methods in ad hoc Networks, *Electronics and Electrical Engineering.* Vol. 97, Issue 1, pp. 33–38.

Cohen, M., S., 2012. Increasing Power Consumption Awareness in Critical Communications Sites with Fuel Cells, *IEEE 34th International Telecommunications Energy Conference (INTELEC)*, Scottsdale, AZ, USA.

Corcorana, B., A., Jenkinsb, N., Jacobson, M., Z., 2012. Effects of aggregating electric load in the United States, *Energy Policy*, Vol. 46, pp. 399–416

Deacon, C. G., Clarke, H. C., 1993. Use of a Linear Offset Hall-Effect Transducer in Student Laboratory Experiments to Measure Magnetic-Fields, *American Journal of Physics*. Vol. 61. Issue 10.pp. 947–948.

Dodiu E., Graur A., Gaitan V. G., 2010. Hard-Soft Real-Time Performance Evaluation of Linux RTAI Based Embedded Systems, *Electronics and Electrical Engineering*. Vol 104, Issue 8, pp. 51–56.

Gao, G., Peng, F., 2010. Reactive Power Reduction at Converter Level, *Proceedings of the 5th IEEE Conference on Industrial Electronics and Applications, (ICIEA 2010)*, Vol 2, pp. 592-597.

Kami, Y., Xiao, F., Murano, K., Mode-Port-Network Approach to Analyze Power-Line EMC Problems for PLC, *20th International Zurich Symposium On Electromagnetic Compatibility*, PP. 73-76, 2009

Krejcar, O., Tucnik, P., Adamec, O., 2011. Evaluation of aJile aJ-80 Real-Time embedded platform for RT-Java parameters, *Measurement*, Volume 44, Issue 7, 2011, pp. 1253-1260

Krejcar, O., Frischer, R., 2011. Real Time Voltage and Current Phase Shift Analyzer for Power Saving Applications”. *Sensors*. vol. 12, Iss. 8, pp. 11391-11405, 2012. DOI 10.3390/s120811391.

Rao, G. V. S. K., Vaisakh, K., 2006. Optimal real and reactive power allocation for real power loss and marginal cost reduction, *Proceedings of the Sixth IASTED International Conference on European Power and Energy Systems*, Rhodes, Greece, JUN 26-28, 2006, pp. 51-56.

Rathika, P., Devaraj, D., 2010. Artificial Intelligent Controller based Three-Phase Shunt Active Filter for Harmonic Reduction and Reactive Power Compensation, *International Multiconference of Engineers and Computer Scientists (IMECS 2010)*, Lecture Notes in Engineering and Computer Science, pp. 1170-1175

Tutsch, M.; Vojcinak, P.; Koziorek, J.; Skrepek, M. Using Automated Evaluation of Efficiency for Photovoltaic Power Plant. In Proceedings of the IEEE 16th Conference on Emerging Technologies and Factory Automation (ETFA), Toulouse, France, 5–9 September 2011; pp. 1–4.

Welchko, B. A., Analytical calculation of the RMS current stress on the DC link capacitor for a VSI employing reduced common mode voltage PWM, 2007 *European Conference On Power Electronics And Applications*, pp. 2232-2239, 2007

Wurtz, E., Mora, L., Inard, C., 2006. An equation-based simulation environment to investigate fast building simulation, BUILDING and ENVIRONMENT, vol. 41, Issue: 11, pp. 1571-1583.

Yang, S. X., 2008. Forecasting increasing rate of power consumption based on immune genetic algorithm combined with neural network, *Journal of Central South University of Technology*, Vol. 15, pp. 327-330, DOI: 10.1007/s11771-008-0481-1

Zhao, J. J., Li, X., Hao, J. T., Zhang, C. L., Lu, J. P., 2009. Wind Farm Reactive Power Output Optimization for Loss Reduction and Voltage Profile Improvements, *6th IEEE International Power Electronics and Motion Control Conference*, Wuhan, Peoples Republic of China, MAY 17-20, 2009, Pages: 1453-1457.