Interconnection Optimalization of Power Units with Renewable Power Sources (RES) to Distribution Network

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Abstract:

This doctoral thesis deals with renewable power sources (RES) which can be connected to the distribution power network in the Czech Republic and in Spain. We mean photovoltaic cells, wind plants, small water power plants, biomass power plants and so on. I try to draw up a specification of problems of renewable energy sources and their power control, because these sources have certain specific features that are given by their characters. I give an attention to the characteristics of the sources that influence the reliability and quality of the power supply. I also deal with this behavior of sources in the distribution grid, their possible influence on a voltage regulation, influence of their power variation on voltage waveform at the point of connection and also an examination of different variants of grid topology for which these sources work considering their operation utility.

Keywords:

Microgrids, renewable energy, renewable power sources, optimalization, wind power, PV cells, fly-wheels, water power plant, mathematical model of sources, load waveform, Swing

Contents

1 INTRODUCTION

As conventional fossil-fuel energy sources diminish and the world's environmental concern about acid deposition and global warming increases, renewable energy sources (solar, wind, tidal, and geothermal, etc.) are attracting more attention as alternative energy sources. Among the renewable energy sources solar photovoltaic (PV) energy has been widely utilized in small-size applications. It is also the most promising candidate for research and development for large-scale uses as the fabrication of less-costly photovoltaic devices becomes a reality. PV power generation, which directly converts solar radiation into electricity, contains a lot of significant advantages such as inexhaustible and pollution-free, silent and with no rotating parts, and size-independent electricity conversion efficiency. Positive environmental effect of photovoltaic is replacing electricity generated in more polluting way or providing electricity where none was available before. With increasing penetration of solar photovoltaic devices, various anti-pollution apparatuses can be operated by solar PV power; for example, water purification by electrochemical processing or stopping desert expansion by photovoltaic water pumping with tree implantation. From an operational point of view, a photovoltaic array experiences large variations of its output power under intermittent weather conditions. Those phenomena may cause operational problems at a central control centre in a power utility, such as excessive frequency deviations, spinning reserve increase, etc.

One method to overcome the above problem is to integrate the PV power plant with other power sources such as diesel backup, fuel cell backup, battery backup, and superconductive magnetic energy storage (SMES) backup. The diesel backup for PV power is able to make a continuous 24-hour power supply be possible. However, it has a couple of severe drawbacks. Its electricity efficiency decreases significantly at a low level of power output, and the diesel power generation is environmentally detrimental as well. The SMES technology is many years from commercialization, and there is a significant potential health risk associated with the technology because of its strong magnetic field generation.

Almost all the electricity currently produced in the Czech Republic (Spain) is generated as part of a centralised power system designed around large fossil fuel or nuclear power stations. This power system is robust and reliable but the efficiency of power generation is low, resulting in large quantities of waste heat. The principal aim of this project is to investigate an alternative concept:

the energy production by small scale generators in close proximity to the energy users, integrated into microgrids.

2 MICROGRID

General definition - a microgrid is an integrated energy system consisting of interconnected loads and distributed energy resources which as an integrated system can operate in parallel with the grid or in an intentional island mode1.

Microgrids is the decentralised electricity generation combined with production of heat - bear the promise of substantial environmental benefits, brought about by a higher energy efficiency and by facilitating the integration of renewable sources such as photovoltaic arrays or wind turbines. By virtue of good match between generation and load, microgrids have a low impact on the electricity network, despite a potentially significant level of generation by intermittent energy sources.

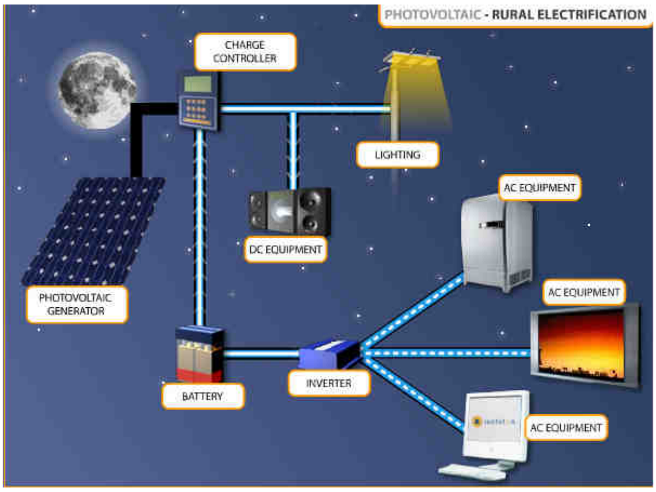

Figure 1: Stand-alone microgrid at night

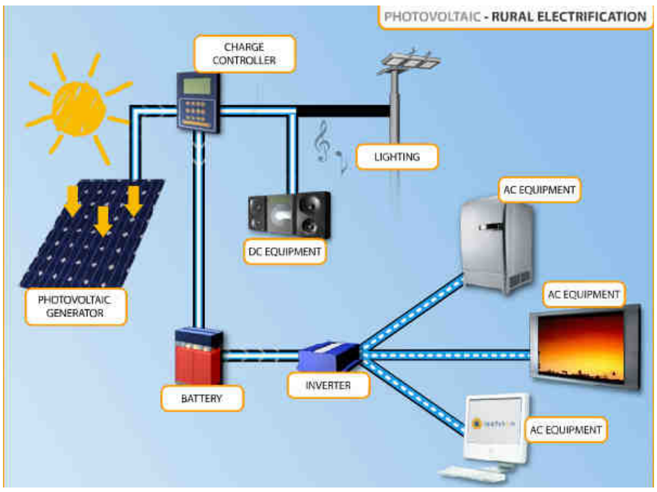

Figure 2: Stand-alone microgrid in the day-time

A microgrid is a small-scale power supply network that is designed to provide power for a small community, for example a typical housing estate, isolated rural communities, to mixed suburban environments, academic or public communities such as universities or schools, to commercial areas, industrial sites and trading estates, or municipal regions.

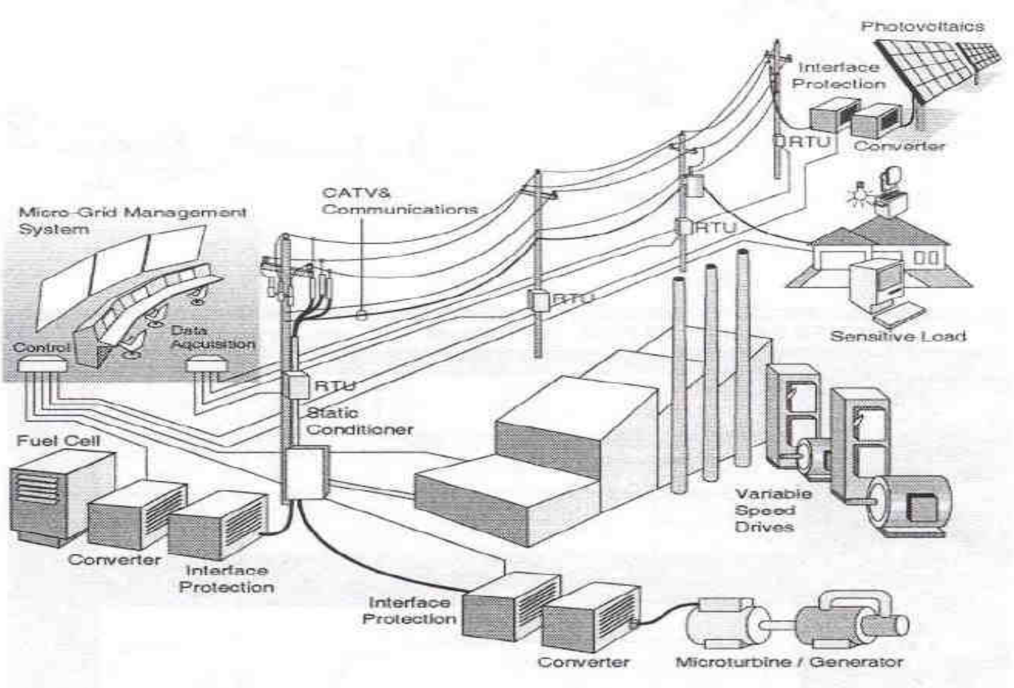

Figure 3: Electric power network - microgrid

Advantages and disadvantages of microgrid

The use of renewable energy sources for the generation of electricity is seen as one of the important ways of reducing carbon dioxide emissions. Whilst some of these sources can produce large power outputs in single power stations – for example hydropower or geothermal power. The majority are relatively small in size. This means such generators are more conveniently (and cheaply) connected at lower voltages within the distribution system. It was never envisaged that this system would be required to support the connection of generation. A similar situation exists with combined heat and power (CHP) units which produce both electricity and heat. Approximately, almost 50% of the primary energy consumption is used to provide heating and hot water in buildings and the aim of CHP is to supply this low-grade heat alongside electricity generation. The advantages of a high overall efficiency of energy production which are thus attained must be offset against the necessity to operate smaller units close to the consumer, and the usually the need to operate a district heating system to distribute the heat.

The term “distributed generation” is used to describe these generators (typically small renewables and CHP but also other on-site electricity generators) connected to the distribution system. A synonymous term also used is “embedded generation”, describing generators embedded within the distribution system. Connection of generation in this way poses many technical, commercial and safety issues; all of which must be tackled in order to allow a wide penetration of renewable generation. In addition to the problems posed by distributed generation, the use of renewable sources and CHP usually adds more specific issues related to the actual method of generation used. An example that can be used to illustrate this point is photovoltaic (PV) generation. There is no generation at night, which is of course predictable but in addition, the sun can be obscured by cloud cover on a random basis. A similar situation exists with CHP which is normally controlled to supply heat, with electricity production as a by-product. These phenomena change in all time scales leading to a constantly changing electrical output. As a source of electrical energy this has some disadvantages which, in the present format, have to be addressed by the operators of the public electricity supply. Consumers have become used to electrical power available on demand. They do not need to structure their load pattern, the entire responsibility for matching power and demand is placed upon the utilities which must have enough generation available at all times. With more creative thinking about the way energy is supplied, used and controlled it may be possible to satisfy the demand for energy but accommodate the fluctuating resources which are a feature particularly of renewable energy sources. This may be possible by ensuring a satisfactory mixture of sources and loads to enable the demand and supply to match.

Problems of microgrids

Although examples of networks similar to microgrids exist, there are technical and regulatory issues that need to be considered before this concept can apply on a wider scale. The principal issue to consider is how closely the energy supply (both electricity and heat) within the microgrid can satisfy the local loads. The answer to this question will help decide how the microgrid interacts with the main utility, and the nature of the connection to be determined. Indeed, it may even be desirable in some circumstances for the microgrid to be disconnected from the utility, and operate as “stand-alone”. The issues that must be resolved to permit this type of operation include:

1. Precise energy and power balance within the microgrid, on a time scale ranging from milliseconds to years. Over the short time scale, the power balance is linked to the question of control; over longer time scales, one needs to consider the relationship between energy supply,

demand and storage. Similar arguments are used to design stand-alone power supplies, for example, photovoltaic or hybrid systems which power remote equipment or serve isolated rural communities across the world.

2. The nature of connection with the main utility (the “grid connection”). An arrangement which would permit the microgrid operator the choice to operate in the “grid connected” or “stand alone” mode is an uncharted territory for conventional power utility engineers, and issues remain both at the technical and regulatory level.

3. Energy storage. The conventional utility supply operates on the principle that power is generated when it is required. Energy storage introduces a novel component in a utility supply and broadens the design criteria. On a quantitative level, the size of the energy store is intimately linked to the energy balance and to the required security of supply provided by the microgrid.

4. Demand management. The temporal mismatch between generation and load can be alleviated by managing the demand. The shifting of load facilitates achieving the energy balance and helps reduce the size of energy storage. Whilst experience exists of demand-side management at industrial level and lessons can be learned from concepts such as storage heating, demand management at the domestic level is attracting much interest in the research community but further experience is needed before routine applications become commonplace.

5. Seasonal match between generation and load Energy storage and demand management can be effective to achieve energy balance at the diurnal time scale. A sufficient energy must be available from the generators to ensure energy balance over longer time scales if a microgrid powered by renewable or other intermittent energy sources such as micro-CHP is to be capable of stand alone operation. This can usually be achieved only by a diversity of generation methods appropriate to the load.

Why to use microgrids?

The motivation behind use of microgrids lies in the potential of the microgrid concept to deliver a significant reduction of CO_2 emissions, for the following reasons:

- The use of both electricity and heat permitted by the close proximity of the generator to the user, thereby increasing the overall energy efficiency

- Significant environmental benefits made possible by the use of low or zero emission generators including PV arrays and fuel cells etc.
- Low impact on the electricity network, by virtue of good match between generation and load, despite a potentially significant level of generation by intermittent energy sources

The feature of the microgrid is that it should be local electricity generation that matches the power requirements in the microgrid. There are various types of generator that may be considered. Photovoltaic cells are attractive if the environment is primarily residential since they may be incorporated into buildings in an unobtrusive manner. Very small scale cogeneration schemes can be based on gas boilers for central heating and domestic hot water. Possible technologies for this are fuel cells or Stirling Engine powered generators. For a microgrid including commercial or light industrial premises then larger cogeneration schemes based on gas turbines or other prime movers may become appropriate.

Energy storage will probably be required to accommodate the variations of available generation and power demand. Short term storage of electrical power will be necessary to help accommodate the rapid fluctuations of load or generation that may be anticipated on a small power network. Over longer time scales, energy management made possible by storage can be used to make the most efficient use of photovoltaic generation or the electricity produced by micro-CHP. Some energy storage may be possible in the form of domestic hot water or as part of space heating.

2.1 The relationship between the microgrid and a local electricity utility

The intention is that the microgrid can be self sufficient, but for security of supply and flexibility it would almost certainly be connected to the local electrical utility network, or even to adjacent microgrids. These links may be bi-directional enabling the import or export of electricity, or, depending on commercial considerations, it might just be a unidirectional flow of power. From the point of view of the microgrid the utility connection might be viewed just as another generator or load.

This raises the question as to whether or not the microgrid should be linked to other networks over a synchronous alternating current (AC) connection. The advantage of a synchronous link would be its simplicity, requiring only an electrical interconnection, circuit breakers and probably a transformer. Lasseter has considered this possibility and shown that in principle it should be possible to run a microgrid with minimal central control of local generation which is able to operate connected to the utility, or, in the event of loss of the connection, move smoothly into stand-alone or island operation with no loss of power to the microgrid. What is perhaps less clear is how the synchronous connection would be re-synchronised once the utility was ready to re-establish the connection.

The alternative approach would be an asynchronous connection using a direct current (DC) coupled electronic power converter. This might be bi-directional, enabling import and export of power or simply device to import power when local resources were inadequate. An advantage of this approach is that it isolates the microgrid from the utility as regards reactive power, load balance etc. Only power is exchanged with the utility, the microgrid is entirely responsible for maintaining the power quality (frequency, voltage and supplying reactive power and harmonics) within its area.

With an asynchronous link the microgrid might be unusual in that all its power will be supplied through electronic inverters. Some generators, such as photovoltaic cells are intrinsically sources of DC and hence need inversion to connect them to an AC network. Others, for example microturbines or Stirling engines may generate AC but are not well suited to operating a synchronous generator because the frequency is unsuitable or variable. Voltage source inverters with suitable control schemes will be required to permit stable operation of the network with many small generators attached. Fortunately advances in power electronics and digital controllers mean that sophisticated control strategies are possible and the cost need not be excessive. Which of these approaches is more appropriate may well depend on the size of the microgrid. It may also depend on the regulatory environment governing the interchange of power between the microgrid and the utility.

2.1.1 Internal control of a microgrid

There are many commercial and political issues concerned with control; however the technical problems of a microgrid must be managed, for the concept to become a reality. The control of a microgrid is intimately tied with the energy and power balance in the microgrid, and the question of energy storage. There are three main parameters – frequency, voltage and power quality - that must be considered and controlled to acceptable standards whilst the power and energy balance is maintained.

2.1.2 Power balance

A power system usually contains no significant energy storage; the generated and dissipated power must therefore be constantly kept in balance. This power balance must be maintained on a cycle by cycle basis if the system is to maintain its frequency. Too much generation and the system accelerates, too little and it slows; neither situation is acceptable.

In a microgrid, frequency stability becomes critical; therefore control is a major concern. There are a number of techniques used to restore the power balance and hence correct the frequency: the use of load shedding, increase in primary generation and recovery of stored energy. All of these are available within a microgrid, but because the system is small the problem is much more difficult to manage to the same standard as is normal in a utility system.

Short term storage of energy is needed to cope with the fluctuations in power demand or accommodate the sudden loss of some generation. A microgrid with many small generators will not be an intrinsically stiff system, unlike a national interconnected utility. The small generators will neither store significant energy in their mechanical inertia, nor will they necessarily respond quickly to sudden changes of load. Short term storage, probably distributed, with the generators will permit the inverters to follow the rapidly changing demand while giving time for the generators to respond, or extra generation to be brought on line or for generators to be closed down. This same storage could be used to help accommodate the diurnal variation of demand.

There are two related issues, firstly quite small power imbalances will produce large frequency excursions and secondly they will happen much more quickly. The first issue may also be an advantage for a microgrid since small energy stores will have significant effects. The second issue means that stored energy recovery must be fast and precise. Since the most probable store, in the near future is likely to be a battery with an inverter, this does not pose an insurmountable problem; such a system is quite fast enough to ensure adequate frequency control.

2.1.3 Frequency

Power system operates at 50Hz and there are obvious advantages in adopting this frequency, whether there is to be a synchronous connection or not. The frequency limits are laid down by law and are relatively tight though not to the same standards as some other power systems. There is however no reason to adopt these standards and some relaxation could be possible (in a non-synchronous system) if it were advantageous. It is doubtful however, that limits larger than ±0.5 Hz could be acceptable. Frequency therefore must be controlled to within these limits.

The “normal” method of frequency control power system is by control of the rotational speed of the synchronous machines supplying the power. Within a large interconnected system, with many synchronous generators, no single machine can control the frequency, there being a flow of "synchronic power" into any machine that is slowed in order to keep it in synchronism. There needs to be a large power imbalance to alter the speed and hence frequency of the system.

The fewer the number of machines, the less stiff the system and frequency control becomes a technical issue. Machines in such a system must be able to respond quickly to load variations in order to preserve the power balance at all times. This means rapid detection of frequency change and fast, accurate control of load generation, or both.

Not all renewable generators are synchronous machines: wind turbines are often induction generators and photovoltaic arrays connect to the system through inverters. These two require very different frequency and load control in order to satisfactorily operate in a system. Inverters can be used to control frequency since the inverter frequency can be controlled independently of load. However, inverters do not behave as rotational synchronous generators and require different philosophies.

2.1.4 Voltage

The system voltage within a large multi generator system is controlled by initially the voltage of the machines but also by the reactive flow. In general, the reactive balance becomes more critical in a smaller system. For example, all reactive demand must be supplied from one generator in a single machine system. This is not strictly true, but adds significantly to cost and control problems if reactive demand has to be compensated by extra static plant.

A conventional distribution system is usually a feeder network, and there is little interconnection. Voltage drop along feeders becomes an issue, as it will vary with load and distance along the feeder. This dictates that any simple microgrid will have to be either small to be satisfactory or be specially designed as an interconnected network.

The voltage and its limits at consumer's terminals are specified by law, but they are reasonably wide. With proper design, production of the correct voltage should not be an insurmountable problem.

2.1.5 Power quality

Control of power quality will be the biggest issue for a microgrid. Voltage dips, flickers, interruptions, harmonics, dc levels, etc. will all be more critical in a small system with few generators. There will need to be a critical appraisal of both the effects and consequences of relaxing and/or enforcing standards in this area.

The distributed generation within the microgrid could enable better control of power quality. With electrical storage together with the distributed generation power quality could be maintained in much the same way as is achieved by Uninterrupted Power Supply (UPS) systems. The electronic inverters can not only supply power at the fundamental frequency, they can also generate reactive power to supply the needs of reactive loads, cope with unbalanced loads and generate the harmonic currents needed to supply non-linear loads.

2.1.6 Energy balance

Little significance is usually attached to the concept of energy balance in a conventional system: the solution is just to add more fuel over time. A microgrid which contains a high proportion of intermittent energy sources - be it renewables such as PV or wind or energy sources controlled for other purposes such as micro- CHP - is not able to do this. The energy available to the system is finite and depends on matters that cannot usually be controlled or even predicted with any certainty.

If such a source is to be used and achieve levels of reliability similar to those of conventional plant, energy storage is essential. It is also clear that, as the diversity of the generation methods in any system is reduced, the role of energy storage becomes more dominant. It therefore appears desirable that any microgrid should employ more than one method of generation as well as some form of energy store.

The diversity of generation methods is particularly important if the microgrid is to operate stand alone. The microgrid must then contain sufficient generation capacity and type that can supply adequate amounts of energy with sufficient reliability. Photovoltaic arrays, for example, are a reliable power source during the summer months. They combine well with generators such as micro-CHP which generate most power in winter to provide heat for domestic dwellings.

2.1.7 Energy storage

There is no economic general purpose method for the storage of electricity per se in the quantities required for public utility use. There are of course methods involving capacitors and super conducting magnets; both of which are technically complex and with present knowledge, rather expensive, but nevertheless used in specific situations. Because the direct storage of electricity is not very practical, the storage of energy by other methods, for later use in electricity generation is employed. These are many and varied, depending upon the situation and the purpose for which the electricity is to be used.

It is likely that a microgrid will rely on chemical energy storage in the form of electric batteries. In the simplest of systems this will mean lead acid cells, which are well developed, available, predictable and robust. For more sophisticated applications, redox batteries are becoming available, and development will continue. In critical situations, where cost is not an issue, the application of super conducting energy storage has been used. Again, continued development is expected to both reduce costs and to increase reliability. Over shorter periods of time, the use flywheels may be appropriate.

The calculation of battery size (energy), and inverter rating (power), will depend on the size of the loads and generators within the microgrid, as well as its topography. As an alternative to storing energy, the shedding of load is more likely to be used in a microgrid, rather than a large scale public utility, because it is easier to identify those loads which are least critical. Where cogeneration is used, some of this energy storage may well be in the form of heat. This storage could be in the form of domestic hot water or stored for use in space heating. Innovative control strategies can be developed to make use of this storage and, if necessary, the plant may be run to meet the electrical load when there is no demand for thermal energy.

3 PARTS OF MICROGRIDS

3.1 PV cell

As PV cell manufacturing technologies improve steadily, commercial applications of PV power generation have increased from stand-alone to utility-connected generating systems. Interconnection and operation of a PV power unit are not same as electric utilities have been doing for the conventional power plants. It requires specific PV interface, protection schemes, storage devices, and control mechanisms. Especially because the PV power output is directly affected by the changes of weather (solar intensity, temperature, etc.), it becomes considerably complicated to efficiently control the PV power plant.

Solar cells represent the fundamental power conversion unit of a photovoltaic system. They are made from semiconductors, and have much in common with other solid-state electronic devices, such as diodes, transistors and integrated circuits. For practical operation, solar cells are usually assembled into modules.

Many different solar cells are now available on the market, and yet more are under development. The range of solar cells spans different material and different structures in the quest to extract maximum power from the device while keeping the cost to a minimum. Devices with efficiency exceeding 30% have been demonstrated in the laboratory. The efficiency of commercial devices, however, is usually less than half this value.

Crystalline silicon cells hold the largest part of the market. To reduce the cost, these cells are now often made from multicrystalline material, rather than from the more expensive single crystals. Crystalline silicon cell technology is well established. The modules have along lifetime (20 years or more) and their best production efficiency is approaching 18%.

Cheaper (but also less efficient) types of silicon cells, made in the form of amorphous thin films, are used to power a variety of consumer products. You will be familiar with the solar-powered watches and calculators, but larger amorphous silicon solar modules are also available.

A variety of compound semiconductors can also be used to manufacture thin-film cells (for example, cadmium telluride or copper indium diselenide). These modules are now beginning to appear on the market and hold the promise of combining low cost with acceptable conversion efficiencies.

A particular class of high-efficiency solar cells from single crystal silicon or compound semiconductors (for example, gallium arsenide or indium phosphide) is used in specialised applications, such as to power satellites or in system which operate under high-intensity concentrated sunlight.

Photovoltaic materials are not restricted to semiconductors. Solar cells are now available which convert light to electricity by organic modules, with best conversion efficiency exceeding 10%.

3.1.1 How solar cells work

The solar cell operation is based on the ability of semiconductors to convert sunlight directly into electricity by exploiting the photovoltaic effect. In the conversion process, the incident energy of light creates mobile charged particles in the semiconductor which are then separated by the device structure and produce electrical current.

Figure 4: shows the diagram of silicon cell, the typical solar cell in use today. The electrical current generated in the semiconductor in extracted by constants to the front and rear of the cell. The top contact structure which must allow light to pass through is made in the form of widely-spaced thin metal strips (usually called "fingers") that supply current to a large bus bar. The cell is covered with a thin layer of dielectric material – the antireflection coating or ACR – to minimize light reflection from the top surface.

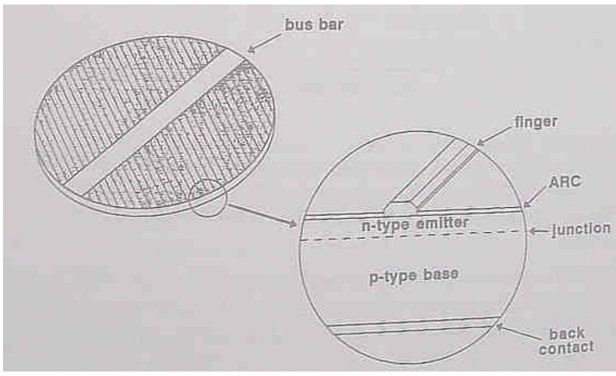

Figure 4: The silicon solar cell

Figure 5 a) shows the band diagram of the semiconductor section under illumination. Light generates electron-hole pairs on the both sides of the junction, in the n-type emitter and in the p-type base. The generated minority carriers – electrons from the base and holes from the emitter – then diffuse to the junction and are swept away by the electric field, thus producing electric current across the device. Note how the electric current of the electrons and holes reinforce each other since these particles carry opposite charges. The p-n junction therefore separates the carries with opposite charge, and transforms the generation current I_l between the bands into an electric current across the p-n junction. The I-V characteristic of a solar cell can be obtained by drawing an equivalent circuit of the device (Figure 6). The generation of current I_l by light is represented by a current generator in parallel with a diode which represents the p-n junction. The output current I is then equal to the difference between the light-generated current I_l and the diode current I_D. Equation

$$I = I_0\left[\exp\left(\frac{qV}{kT}\right) - 1\right]$$

then gives

$$I = I_l - I_0\left[\exp\left(\frac{qV}{kT}\right) - 1\right]$$

Note that, under open circuit when I=0, all the light-generated current passes through the diode. Under short circuit (V=0) on the other hand, all this current passes through the external load. The I-V characteristic and its relationship to the diode characteristic are shown in Figure 6.

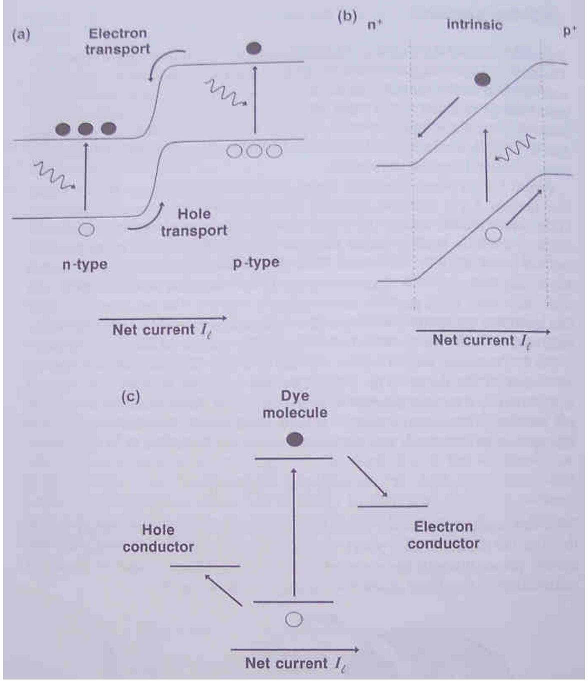

Figure 5: schematic representation of different types of photovoltaic converters. a) Currents in a p-n junction under illumination (applicable, for example, to crystalline silicon or gallium arsenide solar cells), b) the band diagram and operation of p-i-n amorphous silicon solar cells, c) energy conversion by a dye-sensitised photochemical solar cell

The I-V characteristic contains several important points. One is the short-circuit current I_{SC} which, as we noted, is simply the light-generated current I_l. The second is the open-circuit voltage V_{OC} obtained by setting I=0:

$$V_{OC} = \frac{kT}{q} \ln\left(\frac{I_l}{I_O} + 1 \right)$$

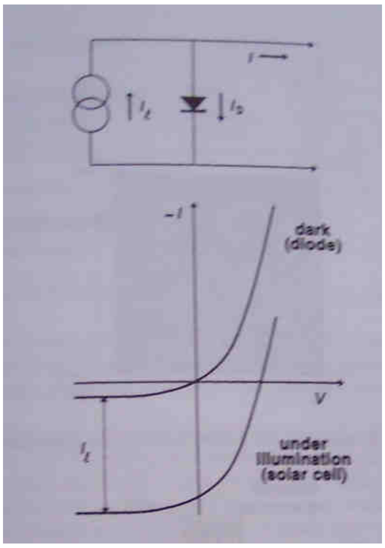

Figure 6: equivalent circuit and I-V characteristic of a solar cell compared to a diode

It is worthwhile to examine this equation in more detail. Both I_l and I_O depend on the structure of the device. However, it is the value of I_O – which can vary by many orders of magnitude, depending on the device geometry and processing-that determinates the open circuit voltage in practical devices.

No power is generated under short or open circuit. The maximum power P_{max} produced by the device is reached at a point on the characteristic where the product IV is maximum. This is shown graphically in Figure 24 where the position of the maximum power point (A) represents the largest area of the rectangle shown. One usually defines the fill factor by

$$P_{\max} = V_m I_m = FF \; V_{OC} \; I_{SC}$$

where V_m and I_m are the voltage and current at the maximum power point.

The efficiency η of a solar cell is defined as the power P_{max} produced by the cell at the maximum power point under standard test conditions, divided by the power of the radiation incident upon it.

Most frequent conditions are: irradiance 100mW/cm^2, standard reference AM1.5 spectrum, and temperature 25°C. The use of this standard irradiance value is particularly convenient since the cell efficiency in percent is then numerically equal to the power output from the cell in mW/cm^2. Other test conditions are sometimes adopted for cells which operate in a different environment, for example, cells which power satellites and operate under AM0 spectrum.

The I-V characteristic which we have derived for a simplified device describes, in fact, rather well the operation of solar cells in practise if the parameters make allowance for the losses which take place in practical devices.

Gallium arsenide solar cells (Figure 7) are, because of their high cost, usually intended for operation on satellites or in concentration system. Gallium arsenide is a direct-gap semiconductor and most photons of light are absorbed in the top emitter layer. The top “windows” layer prevents these carries diffusing to the top surface and being lost by surface recombination.

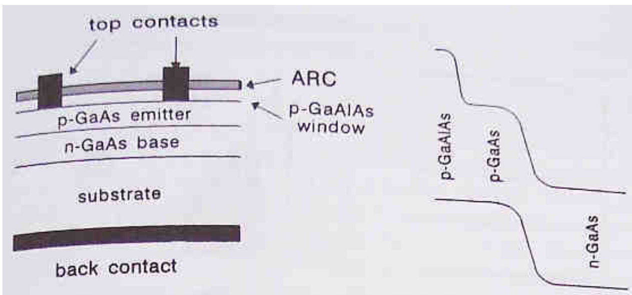

Figure 7: The structure and band diagram of gallium arsenide soalr cells

Most thin-film solar cells are made from amorphous or polycrystalline semiconductors with low diffusion constant for electrons and holes. To aid the carrier transport, these cells usually incorporate a lightly doped or intrinsic layer as part of the junction where most of the light is absorbed. Electrons and holes which are created in this layer are then pulled apart by the electric field immediately after their creation, eliminating carrier diffusion to the junction.

Semiconductors need not form the key element of solar cell operation. Working solar cells have now been manufactured where the charge separation step is mediated by a molecular dye. In these devices, the dye layer covers a nanocrystalline titanium oxide electrode which acts as a receptor for electrons from the photoexcited dye molecules. The nanocrystalline structure of the titanium oxide particles assists efficient light absorption even by a very thin dye layer, which is probably monomolecular. The positive electrode is formed by a hole-carrying redox electrolyte.

3.2 Battery

Another important element of microgrids is the battery. It is necessary in such a system because of the fluctuating nature of the output delivered by the PV arrays. Thus, during the hours of sunshine, the PV system is directly feeding the load, the excess electrical energy being stored in the battery. During the night or during the period of low solar irradiation energy is supplied to the load from the battery.

3.2.1 Introduction (Lead-Acid Battery)

A storage battery is a chemical device reversible in its action, which stores chemical energy for use later as electrical energy. The chemical energy stored in electrodes of a battery cell is converted to electrical energy when the cell is discharging. Electrical energy is applied to the battery during the operation of charging, so the electric current produces chemical changes in the battery.

The most commonly used storage battery for utility applications is the lead-acid type. The fundamental parts of a lead-acid battery cell are two dissimilar electrodes immersed in an electrolyte, namely

Anode(-) : Spongy lead (Pb)
Cathode(+) : Lead dioxide (PbO_2)
Electrolyte : Dilute solution of sulfuric acid (H_2SO_4)

When a battery cell is connected to a circuit, it allows charge to flow around the circuit. In its external part, the charge flow is electrons resulting in electrical current. Within the cell, the charge flows in the form of ions that are transported from one electrode to the other. The cathode, highly oxidized lead dioxide, receives electrons from the external circuit on discharge. These electrons react with the cathode material, which leaves some lead free to combine with sulphate ions to form lead sulphate. Hydrogen ions move in to the cathode and combine with oxygen to form water. At the anode, reactions between the anode material and the sulphate ions result in excessive electrons that can be donated to the external circuit. In this way the chemical energy stored in the battery is converted to electrical energy.

The chemical reaction occurred at the anode is

$$Pb + SO_4^{2-} \underset{charge}{\overset{discharge}{\rightleftarrows}} PbSO_4 + 2e^-$$

and that at the cathode is

$$PbO_2 + SO_4^{2-} + 4H^+ + 2e^- \underset{charge}{\overset{discharge}{\rightleftarrows}} PbSO_4 + 2H_2O$$

Therefore, the net reaction can be expressed as follows

$$PbO_2 + Pb + 2H_2SO_4 \underset{charge}{\overset{discharge}{\rightleftarrows}} 2PbSO_4 + 2H_2O$$

A battery system is a group of battery cells that supply DC power at a nominal voltage to an electrical load. The number of cells connected in series determines the nominal voltage of the battery system, and the capacity of the battery system is the basic factor in determining the discharge rate. The voltage is the force enforcing each of the electrons coming out of the battery and the capacity is the number of electrons that can be obtained from the battery. While the voltage is fixed by cell chemistry, the capacity is variable depending on the quantity of active materials. The discharge rate of a battery is given in terms of ampere-hours (Ah) to a particular discharge voltage level. For the lead-acid battery, its nominal cell voltage is 2V and the nominal discharge voltage level is 1.75 V/cell, or approximately 87.5 % of the nominal cell voltage rating. The equivalent circuit for a battery is shown in Figure 8.

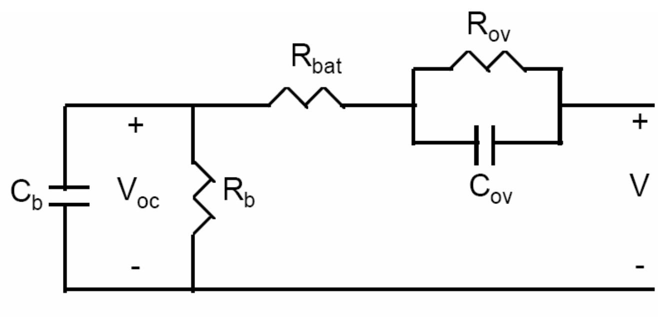

Figure 8: Equivalent circuit for a battery

R_{ov} - overvoltage resistance
C_{ov} - overvoltage capacitance
R_{bat} - internal resistance
R_b - self-discharge resistance
C_b - battery capacitance
V_{oc} - open circuit voltage
V - battery voltage

The internal resistance is due to the resistance of electrolyte and electrode. Self-discharge resistance is a result of electrolysis of water at high voltages and slow leakage across the battery terminals at low voltages. The over-voltage is simulated as an RC circuit with a time constant in the order of minutes. Lead-acid battery systems are a near-term solution to power regulation needs for electric utilities. However, the technology has suffered from a slow acceptance into power markets due to such factors as uncertain return on investment and difficulty in quantifying benefits. Recently, there is worldwide interest to develop alternatives to lead-acid batteries that are able to produce high performance at low cost. Advanced batteries such as nickel-cadmium, sodium-sulfur and zinc-bromine are likely to emerge in the next decade.

3.2.2 Nickel-Cadmium Battery

As the nickel-cadmium battery promoters claim its superiority over the lead-acid batteries in spite of the high capital cost, there are several tries to adopt the nickel-cadmium batteries for use in PV applications. One major reason for that is its longer life and operational reliability. It is undamaged by complete discharge and overcharge.

The active material of the cathode is nickel hydrate with graphite and that of the anode is cadmium sponge, with additives to aid conductivity. The electrolyte is a solution of potassium hydroxide (KOH), including a small amount of lithium hydroxide (LiOH) to improve capacity. The charge-discharge reaction may be written as

$$2Ni(OH)_3 + Cd \underset{charge}{\overset{discharge}{\rightleftarrows}} 2Ni(OH)_2 + Cd(OH)_2$$

The nominal voltage of a nickel-cadmium battery on discharge is 1.2 V. When the battery is connected to an external load, its voltage falls to a value depending on discharge rate and state of charge. The normal final discharge voltage is 1.05 V/cell. The battery is characterized by a low self-discharge rate; its capacity drops to about 80 % in a year under open circuit conditions. Its operating temperature range is between -50 to 60 °C and the battery capacity drops to half of the nominal capacity at -50 °C.

Nickel-cadmium battery system contains its significant features for PV applications. With respect to charging conditions, the nickel-cadmium battery offers more than 80% charging efficiency, as high as a lead-acid battery does. It does not suffer from complete discharge or overcharge in contrast to the lead-acid battery and its annual maintenance is less costly that that of the lead-acid battery. At low temperatures there is a need for the lead-acid battery to be kept in a high state of charge to avoid freezing, which would make it less cost effective over the nickel-cadmium battery.

A disadvantage associated with the nickel-cadmium battery is its memory effect and high capital cost. Repeated use in the same way causes the battery to adjust itself to a certain capacity in relation to its load. Its cost per ampere-hour of capacity is considered as another disadvantage for wide use although the battery is promoted as an alternative to the lead-acid battery in PV applications.

3.2.3 Sodium-Sulfur Battery

The sodium-sulfur battery operates at relatively high temperature ranging from 300°C to 380°C in order to maintain the sodium, sulfur and reaction products in liquid forms and to obtain adequate electrolyte conductivity. Unlike conventional battery systems that consist of solid electrodes and liquid electrolytes for the reaction medium, the sodium-sulfur battery is based on liquid electrodes and a β-alumina (Al_2O_3) solid electrolyte. The battery uses molten sodium and molten sulfur as active materials for the anode and the cathode, respectively. Its operation relies on the property of β-alumina, which combines very low electronic conductivity with an unusually high ionic conductivity, especially to sodium ions. The overall chemical reaction can be written as

$$2Na + 3S \underset{charge}{\overset{discharge}{\rightleftarrows}} Na_2S_3$$

The operating discharge voltage characteristics are somewhat lower than those of lead-acid batteries. The sodium-sulfur battery would start at around 1.9 V and finish at about 1.4V.

The sodium-sulfur battery possesses several potential advantages for energy storage applications. It is capable of quick responses to sudden changes from charge to discharge conditions and vice versa, as well as sudden changes in load demand. Its capital cost is projected to be low compared to other advanced battery systems because the battery component materials are relatively abundant and inexpensive. A projected installation cost of $100/kWh is believed achievable. Energy efficiency of the sodium-sulfur battery is high at approximately 80% and it does not self-discharge. It possesses high volumetric energy density. The projected energy density of the battery is about 200Wh/kg compared to 35Wh/kg for lead-acid batteries.

There are a number of technical issues including cell reliability that must be addressed before the technology is ready for commercial introduction. Because sodium and sulfur are hazardous materials, safety and environmental concerns must be considered in its fabrication, operation and disposal.

3.2.4 Zinc-Bromine Battery

The zinc-bromine battery is another promising system for PV power applications due to inherent chemical simplicity, good electrochemical reversibility of the electrodes and low-cost material. It is a near-ambient temperature, flowing electrolyte system. Its active materials are stored externally in anolyte and catholyte reservoirs. Upon charging the battery, an electrolyte solution of zinc bromine ($ZnBr_2$) is passed through the battery with the aid of a circulator. As dc electricity is passed through the battery, zinc metal is deposited on the anode, and bromine gas is generated at the cathode and then is carried away with the circulating electrolyte stream. Upon discharge, circulation of the aqueous zinc bromine electrolyte carries bromine to the cathode of the stack and current may be withdrawn from the battery. Microporous polyethylene separators are used to slow the direct reaction of the bromine-rich stream with zinc. The overall cell reaction is written as

$$Zn\ \text{(s)} + Br_2\ \text{(g)} \underset{charge}{\overset{discharge}{\rightleftarrows}} ZnBr_2\ \text{(aq)}$$

where s, g, and aq denote solid-, gas-, and aqueous-states, respectively. There are several attributes of the zinc-bromine battery for applications of future energy storage. The majority of the battery's components are made of low-cost, plastic materials. Inexpensive construction materials coupled with low fabrication expenses result in favorable capital cost projections. It can be assembled in modular fashion using standard cell stacks, allowing the user to increase capacity to meet future requirements. The near-ambient temperature operation does not require the complex thermal management necessary in some high-temperature systems. It can be repeatedly deep discharged without performance deterioration. Its energy efficiency is not as high as that of the competitors, roughly 60-70 %.

However, there are a number of key technical issues related to the reliability and performance of the battery. The efficiency of the battery system is somewhat lower than other systems, due to resistive losses in the separators, electrolyte, and electrodes. The system's mechanical complexity creates a good deal of maintenance requirements including pump repair and stack replacement. Additionally, the safe handling, storage and disposal of zinc-bromine batteries must be considered because bromine is a toxic material.

3.2.5 Battery Applications to Power Systems

The future electric power system is estimated to be uncertain and potential capacity shortages, competitive power markets and increasing environmental regulations will create further stresses on the interconnected power network. The roles of storage facilities, especially a battery energy storage (BES) system as power regulation and energy management are being recognized as a practical solution to future operating uncertainty.

BES systems have been interesting power utilities as an option to supply power at peak time to achieve load levelling. Recently, other dynamic benefits of BES have been identified, such as load following, spinning reserve, power factor correction, long line stabilization, and voltage and frequency regulation, etc. The BES system is predicted to become an economically attractive option for utilities in the future due to those benefits coupled with the ability to provide peak power.

3.3 Full cell

It looks exceptional that fuel cells have not been widely commercialized for power utility applications since sulfuric acid fuel cells were invented 150 years ago by an Englishman, William Grove. The great promise of fuel cells as a means for efficient production of electricity from the oxidation of a fuel has been recognized again due to the growing interest in environmental concern about global warming and decreasing conventional power generating sources.

The fuel cell is an electrochemical device that converts the free-energy change of an electrochemical reaction into electrical energy. The simplest overall fuel cell reaction is

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + electricity$$

The free-energy change of this reaction under standard conditions of temperature and pressure (25 °C, 1 atm) is 56,32 kCal/mole. The number of electrons transferred in this reaction is 2 and the reversible potential is 1.229 V. Even if there were no efficiency losses in H_2-O_2 fuel cells, heat would still be rejected from a fuel cell. Thus, the theoretical efficiency of the fuel cells at 25 °C is 83 %.

The performance of a fuel cell that operates at low and intermediate temperatures of 25 - 200 °C is illustrated in Figure 9. That figure, a typical cell voltage versus current density plot, explains the important role of electrode kinetics on its performance. The following relation may represent the performance equations when the current density varies from zero to the end of the linear region.

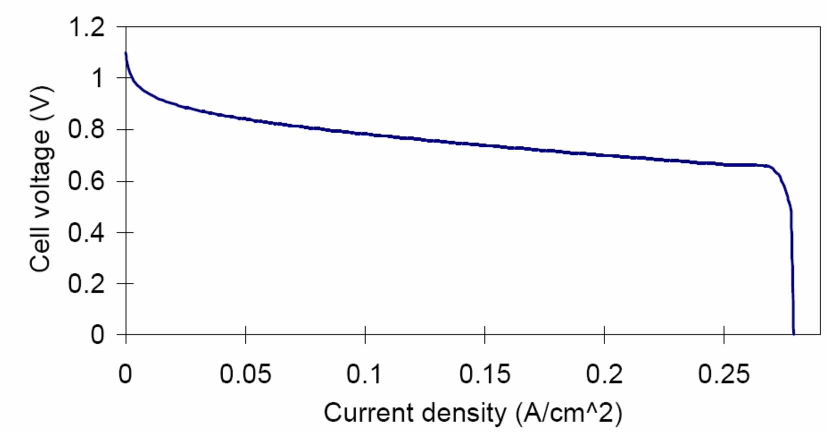

Figure 9: Typical plot of cell voltage vs. current density for a fuel cell

$$E_f = E_{f0} - b \log I_f - RI_f$$

Where

$$E_{f0} = E_r + b \log I_{f0}$$

The low electrocatalytic activity of most electrode materials for the oxygen electrode reaction causes the difficulties in attaining high energy efficiencies and high power densities in low- to medium-temperature fuel cells. Fuel cell performance can be increased by increasing cell temperature and reactant pressure.

The equivalent circuit for a fuel cell is depicted in Figure 10. The equivalent steady state DC resistance is high but the transient impedance is low. The low transient impedance will make fuel cell response much faster than any conventional generating system. It should be remembered that fuel cells will use the same primary fuels as conventional power generation forms, and fuel cells must be economically competitive with these conventional systems. Therefore, fuel cells do not offer a real energy alternative but contribute to energy savings because of their intrinsic high efficiency. The reliability of fuel cells for steady power generation has been proven in the U.S. aerospace program. Design reliability (mean time to failure) greater than 95 % has been achieved consistently under the stringent conditions of space flight. The design reliability required for most terrestrial uses is lower than those needed for aerospace applications. However, terrestrial units require reliability during much longer total operating periods. It is expected that the first generation of commercial fuel cell power generation systems will have an on-stream availability of 90 %. Ultimately, fuel cell power plants can have on-stream availability of 98 - 99 %.

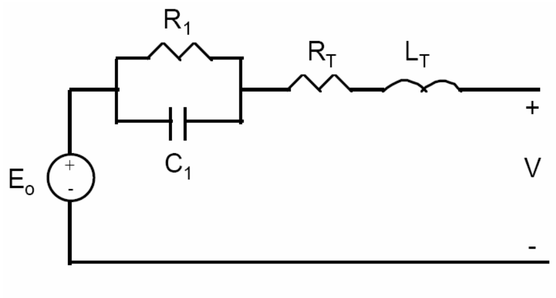

Figure 10: Equivalent circuit of a fuel cell

E_0 - open circuit voltage
R_1 - charge transfer resistance
C_1 - cell capacitance
R_T - electrolyte resistance
L_T - equivalent inductance

The high reliability of a fuel cell system will largely result not only from the modularity of the stacks and stack components, but from their lack of highly stressed moving parts operating under extreme conditions. It operates under relatively benign conditions, so it can be designed such that maintenance is required only at infrequent intervals. A plant could be operated at full power during periods of routine maintenance by replacing spare modules. Without spare parts, plants could be designed so that only partial shutdown will be necessary in the event of failure. Any low-temperature fuel cell system must take several fuel-processing steps to produce hydrogen that will be consumed inside the fuel cell stacks. The most effective way to produce the hydrogen is by steam-reforming of hydrocarbon fuels. First, fuel purification to avoid poisoning of the steam-reforming catalyst is required, which is done by hydrodesulfurization. This is followed by reforming and carbon monoxide (CO) shift reaction to reduce any residual CO values to acceptable levels. The above reactions are endothermic, so they need a net heat input from the fuel used or from any available heat. High-temperature heat is required for the reforming, typically 750 – 800 °C. Unless this heat can be given directly by the waste heat from a high-temperature fuel cell, it must be provided by burning excess fuel.

Fuel cells are known to possess a great number of attributes that make them attractive for the purpose of power generation. The inherent modularity in their production contains the feature less sensitive to size. It enables them to be added successively. Fuel cells have high efficiency and relatively flat efficiency characteristics that make them useful for part-load operation. Fuel cells can utilize a variety of fuels such as natural gas, coal-derived gas, biogas and methanol, and they are able to respond very fast to load changes. Their low noise and emissions and negligible water requirements allow them much more flexibility in siting. Because of those benefits, fuel cells have continuously been under research and development despite their high initial cost right now.

3.4 Batteries or fuel cells – what is better to use

Both batteries and fuel cells have their own unique contributions to electric power systems as discussed above. Those two power sources also contain a great potential to back up severe PV power fluctuations under inclement weather conditions. In this chapter comparison between batteries and fuel cells is carried out in detail only for their PV power backup options, so their common attributes and different attributes will be discussed.

3.4.1 Common Attributes

Photovoltaic power outputs vary depending mainly upon solar insolation and cell temperature. Since control of the ambient weather conditions is beyond human beings' capability, it is almost impossible for human operators to control the PV power itself. Thus, a PV power generator may sometimes experience sharp output power fluctuations owing to intermittent weather conditions, which causes control problems such as load frequency control, generator voltage control and even system stability analysis. There is, therefore, a need for backup power facilities in the PV power generation. Batteries and fuel cells are the most likely technologies to provide the PV system with backup power because these two backup power sources contain some distinct features in common. Those characteristics are listed below.

- Fast load-response capability: Fuel cells and batteries are able to respond very fast to load changes because their electricity is generated by chemical reactions. A 14.4kW lead-acid battery running at 600A has maximum load gradient of 300 A/sec. A phosphoric-acid fuel cell system can match a demand that varies by more than half its rated output within 0.1 second. The dynamic response time of a 20kW solid-oxide fuel cell power plant is less than 4 second when a load increases from 1 to 100%, and it is less than 2 msec when a load decreases from 100 to 1%.
- Modularity in production: Factory assembly of standard cell units provides fuel cell and battery power plants with short lead-time from planning to installation. This modular production enables them to be added in discrete increments of capacity, which allows better matching of the power plant capacity to expected load growth. In contrast, the installation

of a single large conventional power plant may produce excess capacity for several years, especially if the load growth rate is low.

- Highly reliable sources: Due to their multiple parallel modular units and absence of electromechanical rotating masses, fuel cell and battery power plants are more reliable than any other forms of power generation. Fuel cells are expected to attain performance reliability near 85%. Consequently, a utility that installs a number of fuel cell or battery power plants is able to reduce its reserve margin capacity while maintaining a constant level of the system reliability.
- Flexibility in site selection (Environmental acceptability): The electrochemical conversion processes of fuel cells and batteries are very quiet because they do not have any major rotating masses. External water requirement for their operation is, if any, very little while conventional power plants require massive amount of water for system cooling. Therefore, they can reduce or eliminate water quality problems created by the conventional plants' thermal discharges. Air pollutant emission levels of fuel cells and batteries are none or very little. Emissions of SO2 and NO_x in the fuel cell power plant are 0.003 lb/MWh and 0.0004 lb/MWh respectively. Those values are projected to be about 1,000 times smaller than those of fossil-fuel power plants since fuel cells do not rely on a fuel-burning process. These environmentally benign characteristics make it possible for those power plants to be located close to load centers in urban and suburban area. It can also reduce energy losses and costs associated with transmission and distribution equipment. These siting near load centers may also reduce the likelihood of system blackouts.

3.4.2 Different Attributes

Electric current is produced in a storage battery by chemical reactions. The same chemical reactions take place in a fuel cell, but there is a difference between them with respect to fuel storage. In storage batteries chemical energy is stored in the positive/negative electrodes of the batteries. In fuel cells, however, the fuels are stored outside the cells and need to be fed into the electrodes continuously when the fuel cells are required to generate electricity. Other detailed comparison between battery backup and fuel cell backup for PV power supplement is made in the following sections.

Efficiency

Power generation in fuel cells is not limited by the Carnot Cycle in the view that they directly convert available chemical free energy to electrical energy rather than going through heat exchange processes. Thus, it can be said that fuel cells are a more efficient power conversion technology than the conventional steam-applying power generations. Figure 11 illustrates energy conversion processes for a conventional power generator and a fuel cell. Whereas the fuel cell is a one-step process to generate electricity, the conventional power generator has several steps for electricity generation and each step requires a certain amount of energy loss.

Fuel cell power systems have around 40-60 % efficiencies depending on the type of electrolytes. For example, the efficiencies of phosphoric-acid fuel cells and molten-carbonate fuel cells are 40-45 % and 50-60 %, respectively. Furthermore, the fuel cell efficiency is usually independent of size; small power plants operate as efficiently as large ones.

Battery power systems themselves have high energy efficiencies of nearly 80 %, but their overall system efficiencies from raw fuel (mostly coal or nuclear) through the batteries to converted ac power are reduced to below 30 %. This is because energy losses take place whenever one energy form is converted to another. For this calculation, a 35 % of efficiency was assumed for electricity generation from coal or nuclear power stations.

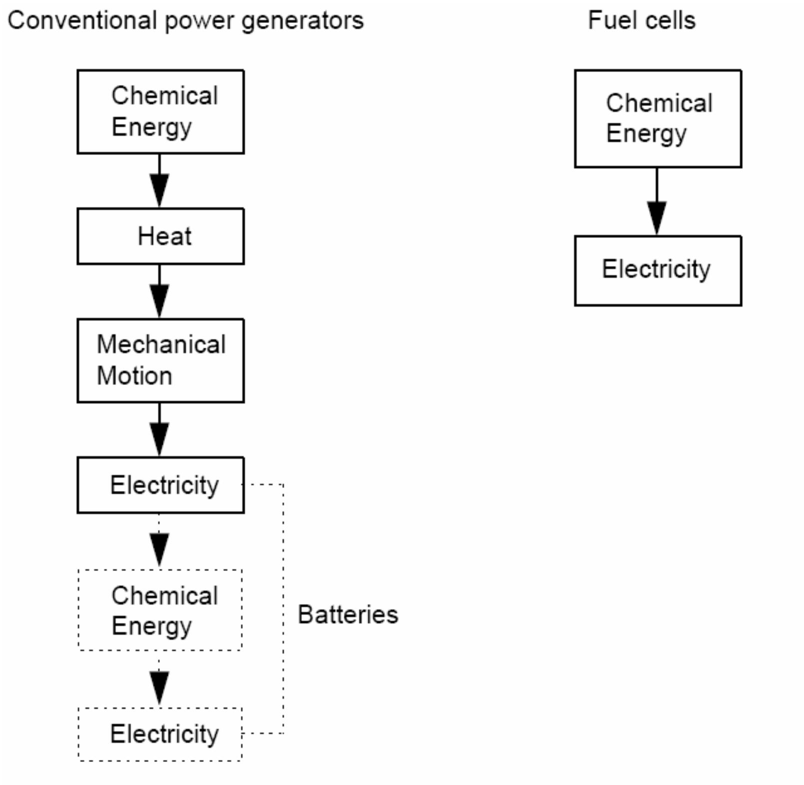

Figure 11: Comparison of energy conversion processes

3.4.3 Capacity Variation

The capacity of a fuel cell is expressed in watts (W), whilst that of a storage battery is represented in ampere-hours (Ah) or watt-hours (Wh). A battery with a rated capacity of 100 Ah at a 10-hr discharge rate can supply 10 A for 10 hours. At discharge rates in excess of 10 A, the battery will provide less than 100 Ah. At less than 10 A of discharge rates, the battery will provide more that 100 Ah. Thus, in specifying the capacity of a battery, it is necessary to note the time rate of discharge.

As the battery discharges, its terminal voltage, the product of the load current and the battery internal resistance (R_{bat}), gradually decreases. The fall of the terminal voltage on discharge is due to its internal resistance. When R_{bat} is constant at given cell temperature and state of discharge, the terminal voltage drop is directly proportional to the load current. However, the internal resistance of a battery varies with its cell temperature and state of discharge. The resistance increases with both fall in cell temperature and depth of discharge.

The decrease in battery voltages with increasing discharge currents is clearly seen in Figure 12.

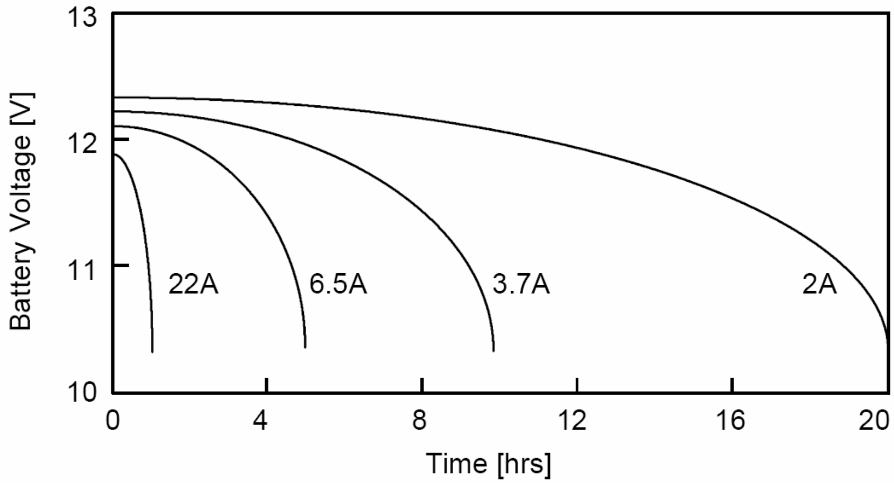

Figure 12: Voltage characteristics of battery at various discharge rates

There is also a reduction in battery capacity with increasing rate of discharge. At 1-hr discharge rate, the available capacity is only 55% of that obtained at 20-hr rate. This is because there is insufficient time for the stronger acid to replace the weak acid inside the battery as the discharge proceeds. Capacity variations at different rates of discharge can be calculated from the curves in Figure 12, and is shown in Table 1.

DISCHARGE RATE [HR]	MEAN VOLTAGE [V]	CURRENT [A]	CAPACITY [WH]	CAPACITY [% WH]
20	**11.85**	**2**	**474**	**100**
10	**11.75**	**3,7**	**435**	**92**
5	**11.55**	**6.5**	**375**	**79**
1	**11.40**	**22**	**251**	**53**

Table 1: Capacity variations of a battery at various discharge rates

For fuel cell power systems, they have equally high efficiency at both partial and full loads as can be seen in Figure 13. The customer's demand for electrical energy is not always constant. So for a power utility to keep adjustment to this changing demand, either large base-load power plants must sometimes operate at part load, or smaller peaking units must be used during periods of high demand. Either way, efficiency suffers and pollution increases. Fuel cell systems have a greater efficiency at full load and this high efficiency is retained as load diminishes, so inefficient peaking generators may not be needed.

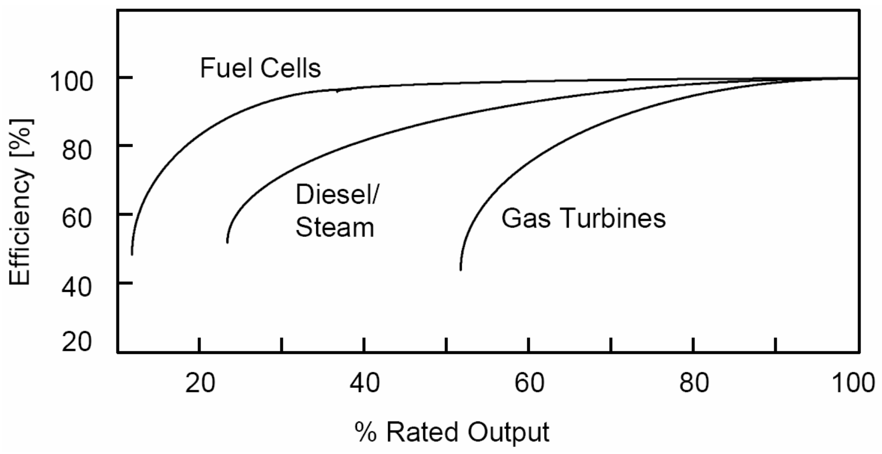

Figure 13: Equally high efficiency of fuel cells at partial and full loads

3.4.4 Flexibility in Operation

Fuel cells have an advantage over storage batteries in the respect of operational flexibility. Batteries need several hours to be taken for recharging after they are fully discharged. During discharge the batteries' electrode materials are lost to the electrolyte, and the electrode materials can be recovered during the recharging process. Over time there is a net loss of such materials, which may be permanently lost when the battery goes through a deep discharge. The limited storage capacity of the batteries implies that it is impossible for them to run beyond several hours.

Fuel cells, on the other hand, do not undergo such material changes. The fuel stored outside the cells can quickly be replenished, so they do not run down as long as the fuel can be supplied. Figure 14 illustrates the energy density of fuel cells compared with lead-acid batteries. The fuel cells show higher energy density than the batteries when they operate for more than 2 hours. It means that fuel cell power systems with relatively small weight and volume can produce large energy outputs. That will provide the operators in central control centers for the flexibility needed for more efficient utilization of the capital-intensive fuel cell power plants. The fuel cell power plants can also be operated as intermediate power generation units during months when coal-fired or nuclear units are under forced outage or on maintenance. Fuel cells use a hydrogen-rich gas to produce electricity. They can employ any fuel that can supply this gas, which includes petroleum, naphtha, natural gas, methanol and biomass. Medium-Btu (British thermal unit) gas from coal gasification or other synthetic fuels may also become an acceptable fuel. In addition, where hydrogen storage is feasible, renewable power sources can drive an electrolysis process to produce hydrogen gas during off-peak periods that will be used to operate the fuel cells during peak demands. The usage of storage batteries in an electric utility industry is expected to increase for the purposes of load leveling at peak loads, real-time frequency control, and stabilizing transmission lines. When integrated with photovoltaic systems, the batteries are required to do another duty.

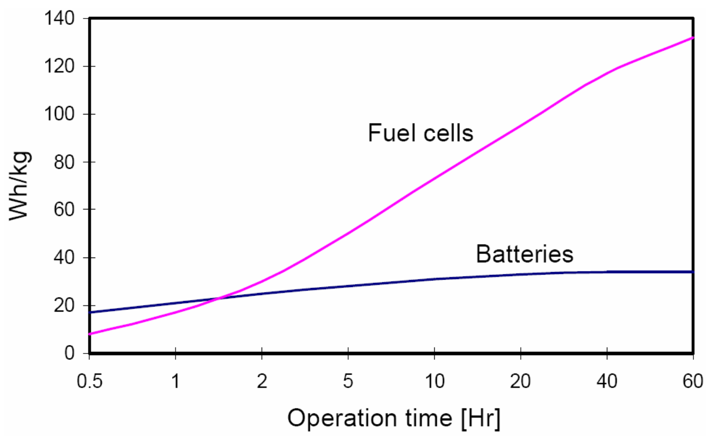

Figure 14: Energy densities for fuel cells and batteries

It is to suppress the PV power fluctuations due to the changes of solar intensity and cell temperature. The fact that the PV power outputs change sharply under inclement weather conditions makes it hard to decide the capacity of the battery power plants since their discharging rates are not constant. For a lead-acid battery, the most applicable battery technology for photovoltaic applications to date, the depth of discharge should not exceed 80% because the deep discharge cycle reduces its effective lifetime. In order to prevent the deep discharge and to supplement varying the PV powers generated on inclement weather days, the battery capacity must be large. From Figure 15, that shows two different PV power variations, the dotted curve requires a larger battery capacity than the other curve. Moreover, the large battery capacity is usually not fully utilized, but for only several days. Fuel cells integrated with photovoltaic systems can provide smoother operation. The fuel cell system is capable of responding quickly enough to level the combined power output of the hybrid PV-fuel cell system in case of severe changes in PV power output. Such a fast time response capability allows a utility to lower its need for on-line spinning reserve. The flexibility of longer daily operation also makes it possible for the fuel cells to perform more than the roles of gas-fired power plants. Gas turbines are not economical for a purpose of load following because their efficiencies become lower and operating costs get higher at less than full load conditions.

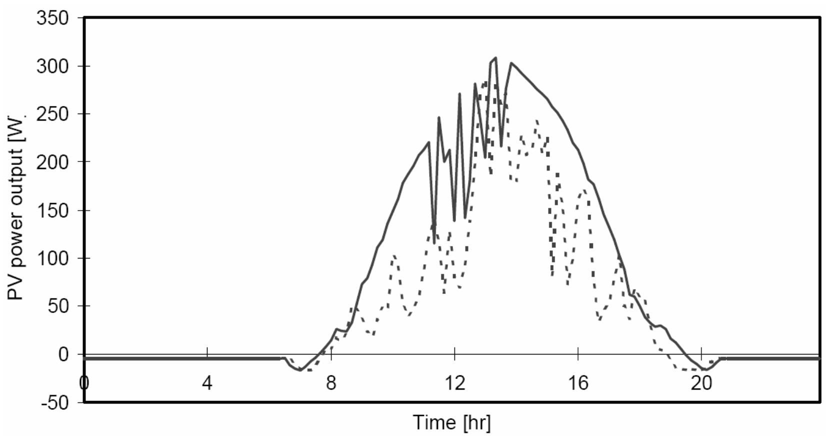

Figure 15: PV power variations requiring different battery capacities

Environmental Externality

During their life cycle operation, fuel cell power plants produce environmental externalities in the process of fuel reforming. However, storage batteries themselves do not contain any environmental impacts even though the battery charging sources produce various emissions and solid wastes. A fuel cell power system emits by far less SO_2, NO_x and other particulates in the fuel reforming process compared to conventional fossil fuel power plants. The amount of CO_2 emissions from the fuel cell system is similar to that from conventional fossil-fuel power plants, but the fuel cell system's high efficiency ranging from 40 % to 60 % results in lower CO_2 emissions. Batteries themselves do not produce any emissions during their operation period even if the power sources providing the batteries with charging power usually at off-peak time generate several chemical emissions and solid wastes. The batteries displace power generation rather than replace it. Therefore, the batteries' environmental impacts should be computed based on the base-load fuel mix used to charge the batteries.

When fuel cell power plants are to be dismantled at the end of their commission, they do not exhibit any detrimental impacts on environment and no specific hazards are encountered. Component recovery rather than waste disposal is likely to be the issue. In phosphoric-acid fuel cells, nickel from the fuel reformer catalyst and platinum from the anode and cathode will require recovery. For molten-carbonate fuel cells, nickel from both the electrodes and the reforming catalysts can be recovered. In solid-oxide fuel cells, nickel and zirconium-containing ceramic components are likely to be recovered.

However, for battery power plants a significant amount of care is required to be taken of their disposal to prevent toxic materials from spreading around. All batteries that are commercially viable or under development for power system applications contain hazardous and toxic materials such as lead, cadmium, sodium, sulfur, bromine, etc. Since the batteries have no apparent salvage value and must be treated as hazardous wastes, disposal of spent batteries is an issue. Recycling batteries is encouraged rather than placing them in a landfill. One method favoring recycling of spent batteries is regulation. Thermal treatment for the lead-acid and cadmium-containing batteries is needed to recover lead and cadmium. Sodium-sulfur and zinc-bromine batteries are also required to be treated before disposal.

3.4.5 Comparing of batteries and fuel cells

Both batteries and fuel cells are able to respond very fast to system load changes because they produce electricity by chemical reactions inside them. Their fast load-response capability can nicely support the sharp PV power variations resulted from ambient weather changes. These two PV power backup technologies also contain some excellent attributes in common, such as modular production, high reliability and flexibility in site selection.

However, there are subtle different attributes between batteries and fuel cells when they are applied to a PV power backup option. Power generation in fuel cell power plants is not limited by the Carnot Cycle, so they can achieve high power conversion efficiency. (Their theoretical maximum efficiency is 83 %.) Even taking into account the losses due to activation overpotential and ohmic losses, the fuel cells still have high efficiencies from 40 % to 60 %. For example, efficiencies of PAFCs and MCFCs are 40-45 % and 50-60 % respectively. Battery power plants, on the other hand, themselves have high energy efficiency of nearly 80 %, but the overall system efficiency from raw fuel through the batteries to the converted AC power is reduced to about 30 %.

A battery's terminal voltage gradually decreases as the battery discharges due to a proportional decrease of its current. A battery capacity reduces with increasing rate of discharge, so its full capacity cannot be utilized when it discharges at high rates. On the other hand, fuel cell power plants have equally high efficiency at both partial and full loads. This feature allows the fuel cells to be able to follow a changing demand without losing efficiency. The limited storage capacity of batteries indicates that it is impossible for them to run beyond several hours. The batteries when fully discharged need several hours to be recharged. For its use in PV power connections, it is as hard as forecasting the weather to compute the exact capacity of the batteries. In order to prevent the batteries' deep discharge and to supplement the varying PV powers on some inclement weather days, the battery capacity should be large, but that large capacity is not fully utilized on shiny days. For fuel cells, they do not contain such an operational time restriction as long as the fuel can be supplied. Thus, the fuel cell power plants can provide operational flexibility with the operators in central control centers by utilizing them efficiently. As intermediate power generation sources, fuel cell power plants may replace coal fired or nuclear units under forced outage or on maintenance.

Storage batteries possess several benefits in peak shaving and load leveling for a power system operation. For those objectives, the batteries' discharge rate is nearly constant at rated value and their capacity can be fully utilized when designed optimally. The battery operation seems to be periodical every day; that is, it charges at system's off-peak and discharges at peak time. Therefore, the batteries can do a great job for those purposes. For the PV power backup the batteries' discharge rate is irregular and their full capacity may usually not be consumed. So, it is difficult to design an optimal capacity of the battery systems for support of the PV power variations and to economically operate them. Instead of batteries fuel cell power plants exhibit diverse operational flexibility for either a PV power backup or a support of power system operation.

Both the battery backup and the fuel cell backup are the most likely technologies to provide backup power for the PV power system in the near future.

3.5 Load

The loads existing in microgrids can be of many types, both DC and AC (heaters, electrical motors, etc.). Most of all loads are AC. The simplest load in real is electrical heater. The heater is a simple resistance controlled by a thermostat. Thus, the load can be simulated as:

$$I_{AC} = \frac{V_{AC}}{R_h}$$

Where IAC is the AC-current and VAC is the AC-voltage of the load, respectively Rh is the resistance of heather, which can be determinated by the rated power Ph_nom and rated voltage Vh_nom of the heater, as follows:

$$R_h = \frac{(V_{h\_nom})^2}{P_{h\_nom}}$$

3.6 Inverter

As known, the PV arrays produce DC power and in many cases we need for AC loads in microgrids AC power, DC/AC conversion is required. The inverter is a converter where the power flow is from the DC to the AC side, namely having a DC voltage, as input, it produces a desired AC voltage as output. It is shown in Figure 16.

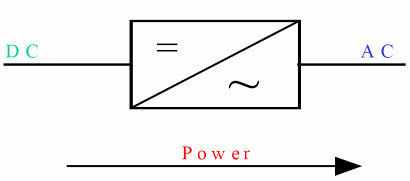

Figure 16: AC/DC inverter

The inverter is characterized by a power dependent efficiency η. The role of inverter is to keep on the AC side the voltage constant at the rated voltage 230 V and to convert the input power Pin into the output power P_{out} with the best possible efficiency. The efficiency of the inverter is thus simulated as:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_{AC} I_{AC} \cos\varphi}{V_{DC} I_{DC}} \Rightarrow I_{DC} = \frac{V_{AC} I_{AC} \cos\varphi}{\eta V_{DC}}$$

Where I_{DC} is the current required by the inverter from the DC side (for example from controller) in order to be able to keep the rated voltage on the AC side (for example on the load). V_{DC} is the input voltage for the inverter delivered by the DC side, for example by the controller.

4 REAL PV SYSTEM ON THE ROOF OF FACULTY OF ELECTRICAL ENGINEERING

4.1 Parameters of PV array

On the roof of building of Faculty of Electrical Engineering in Pilsen is installed 20 kWp PV system which is connected to public grid.

The PV system consists of 192 dark blue monocrystalline silicon solar cell modules which are produced by company Isofoton. The specific color of cells was chosen because of the best efficiency of these cells in the time when the system was installed. There are used 8 single-phase DC/AC converters of SunProfi SP 2500. Power consumption of the inverters is covered by solar system itself and the output is symmetrically phased to building supply grid on 230V/400V. The connection to building grid is directly through switchboard. Own block transformer is not used because of lowering purchase costs. The array is mounted on building roof, situated southbound and inclined in angle 45°. The fixed inclination is compromise for full year operation and low purchase costs.

PV module parameters in producer catalogue www.isofoton.com:
Measurement conditions:
- Radiation: 1000 W/ m2
- Temperature: 25°C

Physical:
- Area of cell: 104,4 cm^2 (cells 103)
- Large SolarModules I-110 (24V)
- Dimension: 1310 x 654 x 39,5
- Weight (kg): 11,5
- Number of cells in series: 72
- Number of cells in parallel: 1
- NOTC (°C): 47
- Type of cell: Monocrystalline Silicon 103 x 103

Electrical:
- Nominal voltage (V): 24
- Maximum power (Wp± 10 %): 110
- Short circuit current (A): 3,38
- Open circuit voltage (V): 43,2
- Maximum power current (A): 3,16
- Maximum power voltage (V): 34,8

The PV array installed on the roof is shown in Figure 17.

Figure 17: PV array on the roof of Faculty of Electrical Engineering in Pilsen

Figure 18: 8 DC/AC inverters

Whole PV system consists 8 the same parts with the same power output. Only one of them has components for measurement and monitoring. For good data evaluation of PV array outputs are measured some values like irradiation on horizontal plane, generator array plane irradiation, ambient temperature in the shade, reference sensor temperature, generator cell temperature, generator voltage, generator current, generator power and inverter AC power out. All these parameters are written down to computer file txt every 10 minutes. We can see in this file also maximum and minimum of all these values for 10 minute time period. Then we can analyze measured values and we can compare these parameters with math model of PV array.

4.2 Measurement of real values of daily irradiation

These presented measurements were made while almost ideal operation conditions for photovoltaic system. That means constant and high level of solar irradiance and good weather conditions.

The measurement is done for a day and night, 24 hours a day by weather station (Vantage Pro - Davis). This system records many different values like humidity of air, speed of wind etc. But the most important to know for model of PV cell are impinging irradiation and ambient temperature. Both these values are recorded in TXT file every 5 minutes. For this model it is sufficient. We can see them for one day in Figure 40. In Figure 19 is shown global daily irradiation during 3 days in summer and in Figure 20 during 3 days in winter. If we compare these graphs, it is clear that, in general, irradiance during winter time is notably lower. Also the period of time a day for measured irradiation in summer is approximately 16 hours but during winter time it is only about approximately 8 hours a day.

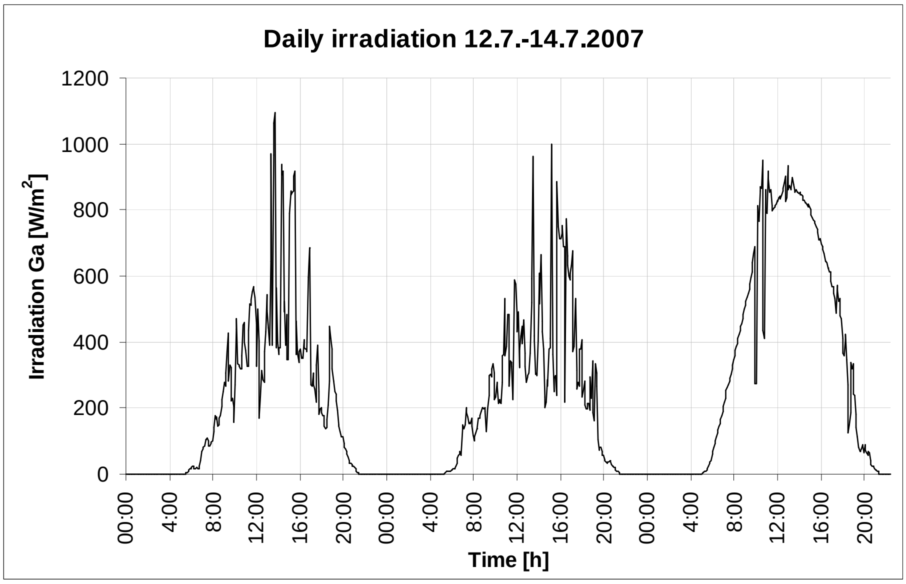

Figure 19: Daily irradiation in summer – 3 days

In Figure 19 the first 2 days the weather was mostly cloudy and only for some short periods of time the Sun was shining. The weather was changed a lot. It is the reason why the curve of irradiation during first 2 days has several peaks. If we imagine average value of this graph in each moment and compare with graph for third day, we can also see difference in maximum values of irradiation for each day between sunny day and partly cloudy days. Detailed graphs are in Figure 21 and Figure 22. We can also notice that impinging irradiance is in a range of 0-1000 W/m^2. For easy imagination we can realize how much energy the PV cells will be able to produce during summer time and winter time because global irradiation is one of the main values how is shown in Figure 40. It is possible to say that surface between the curve of impinging irradiation and axis x is proportional produced energy by PV array. But produced power also depends on type of PV cells, quality of whole PV system etc.

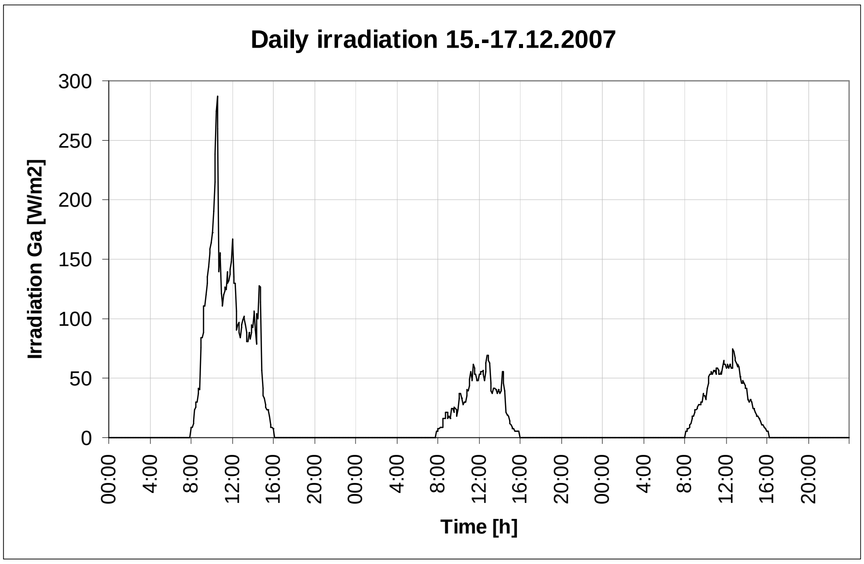

Figure 20: Daily irradiation in winter – 3 days

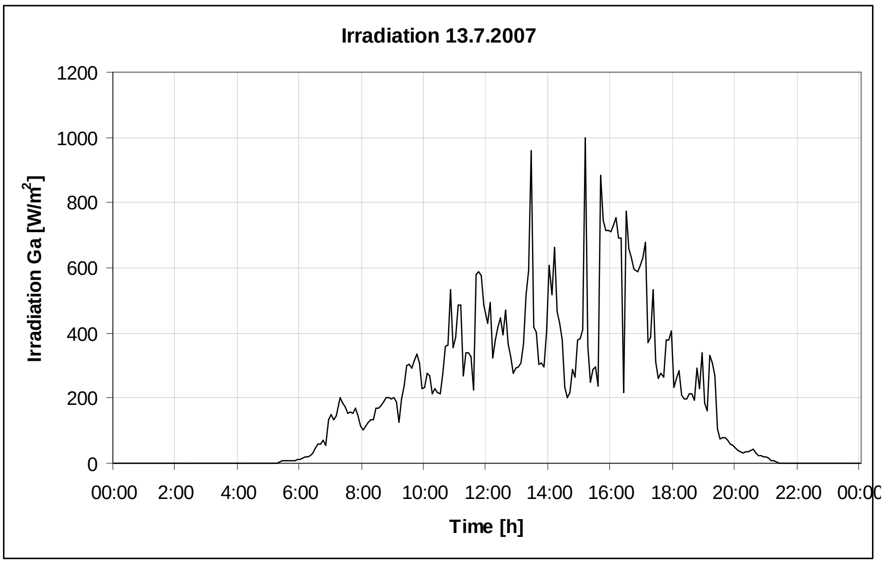

Figure 21: Daily irradiation in summer – 1 day, clouds and occasional sunshine

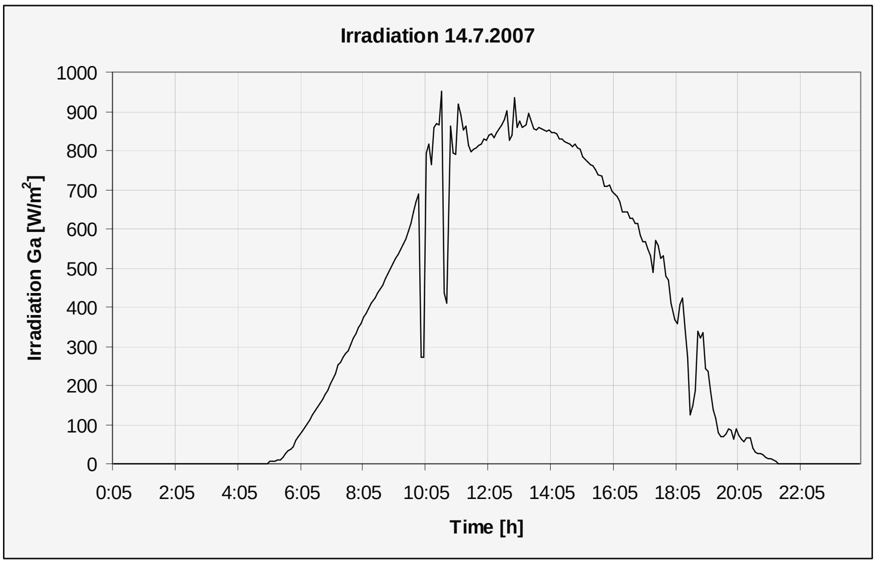

Figure 22: Daily irradiation in summer – 1 day, mostly sunny day

These measured parameters of irradiation will be used like input values for mathematical model of real PV system.

5 MATHEMATICAL MODELLING AND SIMULATION OF PV ARRAY

5.1 Mathematical model of PV cell

We can substitute PV cell by equivalent electric circuit where is included a power supply and diode. The power supply produce the current I_{ph} which depends on impinging radiation. Through diode flows the current I_D. The current I which flows to load is difference between I_{ph} and I_D and it is reduced by the resistance R_S which represents resistance of cell and connection among cells.

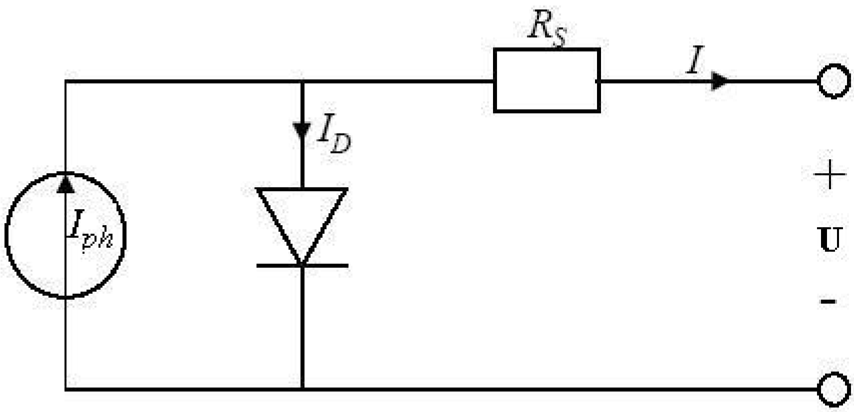

Figure 23: Equivalent electric circuit of PV cell

The cell has constant current while the voltage go up until specific value and after that current go down steeply to zero – diode is opening, I_D go up. It is shown in Figure 24.

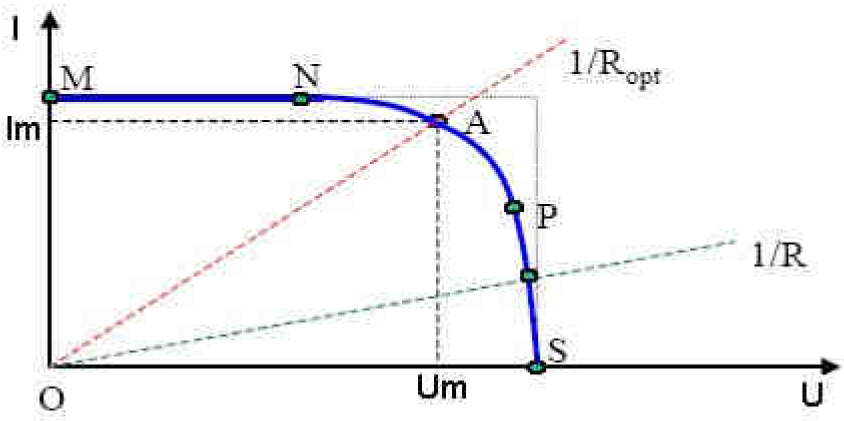

Figure 24: Typical volt-ampere characteristic of PV cell

If we connect a resistive load R to cell then working point of cell will be on crossing point volt-ampere characteristic of cell and load. Volt-ampere characteristic of a load is a straight line with slope 1/R. If value of R is too low, the working point is in area between M and N where cell behaves like constant current source. It is more or less short circuit current. But if value of R is high, the working point is in area between P and S where cell behaves like constant voltage source. It means about a open circuit voltage.

Connection with optimal resistance R_{opt} means that PV cell generates maximum output power which is given to product of voltage U_m and current I_m. Working-point where is the maximum of power and efficiency is in the flexion of volt-ampere characteristic.

In Figure 25, the volt-ampere characteristic of a PV cell for only a certain ambient irradiation G_a and only a certain cell temperature T^c is illustrated. The influence of the ambient irradiation G_a and the cell temperature T^c on the cell characteristics in presented in Figure 26.

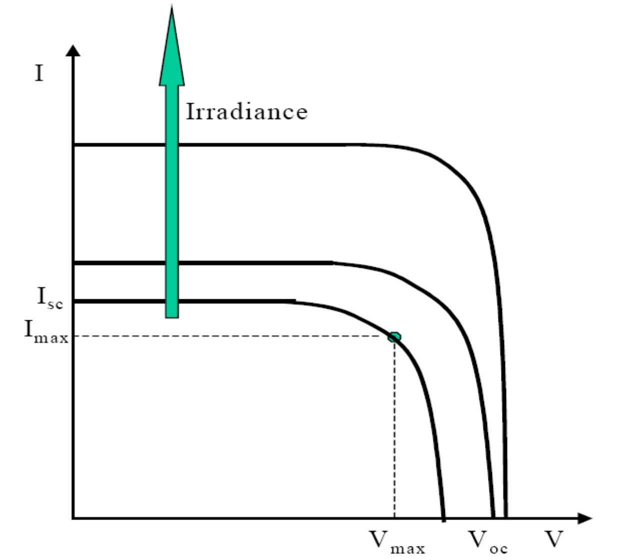

Figure 25: Influence of the ambient irradiation on the cell characteristic

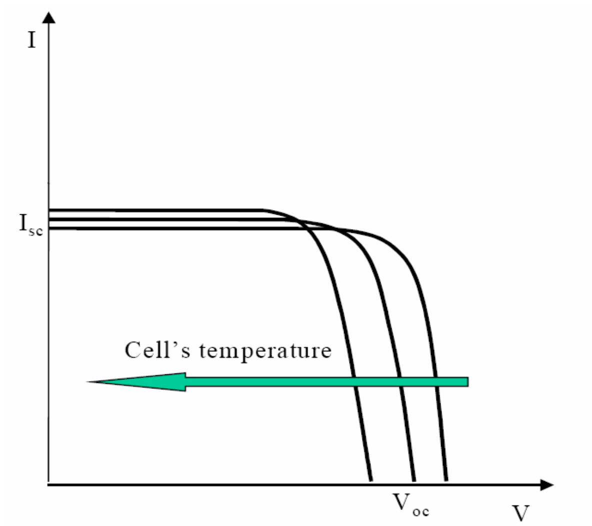

Figure 26: Influence of the cell temperature on the cell characteristic

Figure 25 shows that the open circuit voltage increases logarithmically with the ambient irradiation, while the short circuit current. is a linear function of the ambient irradiation. The arrow shows in which sense the irradiation and the cell temperature, respectively, increase. The influence of the cell temperature on the volt-ampere characteristic is illustrated in Figure 26. The dominant effect with increasing cell temperature is the linear decrease of the open circuit voltage, the cell being thus less efficient. The short circuit current slightly increases with cell temperature.

For practical use, PV cells can be electrical connected in different ways: series or parallel. Figure 27 and Figure 28 present how the volt-ampere curve is modified in the case when two identical cells are connected in series and in parallel.

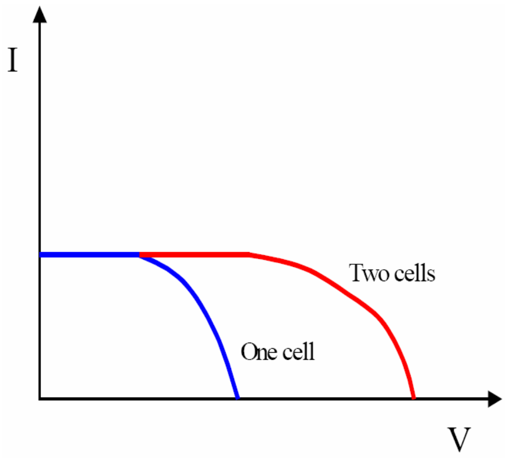

Figure 27: Volt-ampere characteristic of series connection of identical cells

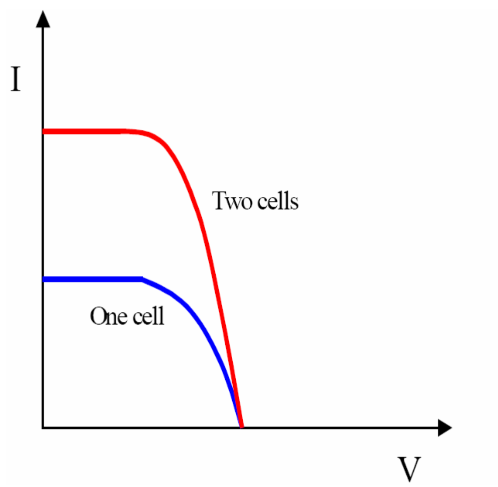

Figure 28: Volt-ampere characteristic of parallel connection of identical cells

It is seen that volt-ampere characteristics of series interconnected cells can be found by adding, for each current, the different voltages of the individual cells. On the other hand, for parallel cells the currents of the individual cells must be added at each voltage in order to find the overall volt-ampere curve.

5.1.1 Parameters of PV cell for normal specification

Standard condition:

Impinging radiation $G_{a,0}$ = 1000 W/m2
Temperature of cell t_{C0} = 22 °C.

a) Short circuit current $I^{C}_{SC,0}$ – the maximum current generated by cell with short-circuited output, (V_C=0).

b) Open circuit voltage $V^{C}_{OC,0}$ – the maximum voltage of cell with disconnected output (I_C=0).

c) Maximum power $P_{Cm,0}$ – maximum power of cell, $P_{Cm,0} = V_{Cm}*I_{Cm}$ [W]

From these parameters we can assign so called the Fill Factor: $FF = V_m*I_m/V_{SC}*I_{SC}$ [-]

The Fill Factor for good cells would be higher than 0,7.

All parameters are valid only for standard condition. If impinging radiation G_a or temperature of cell t^c change, then open circuit voltage, short circuit current and flexion of volt-ampere characteristic change as well.

Parameter change of PV cell by influence of change G and t^c
1) Influence of G

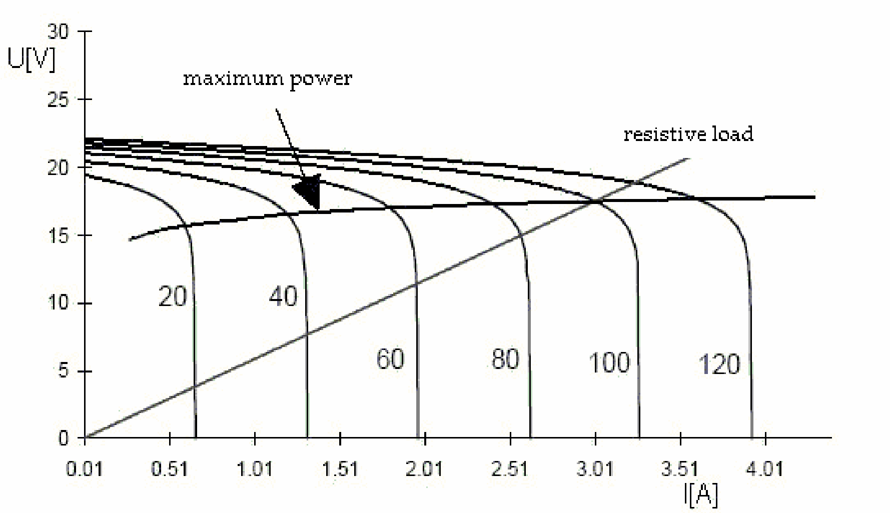

*Figure 29: Influence of radiation change G [(W/m2)*0,1] on current and voltage of PV cell*

Open circuit voltage goes up logarithmic when impinging radiation goes up but short circuit current go up linearly.

2) Influence of tc

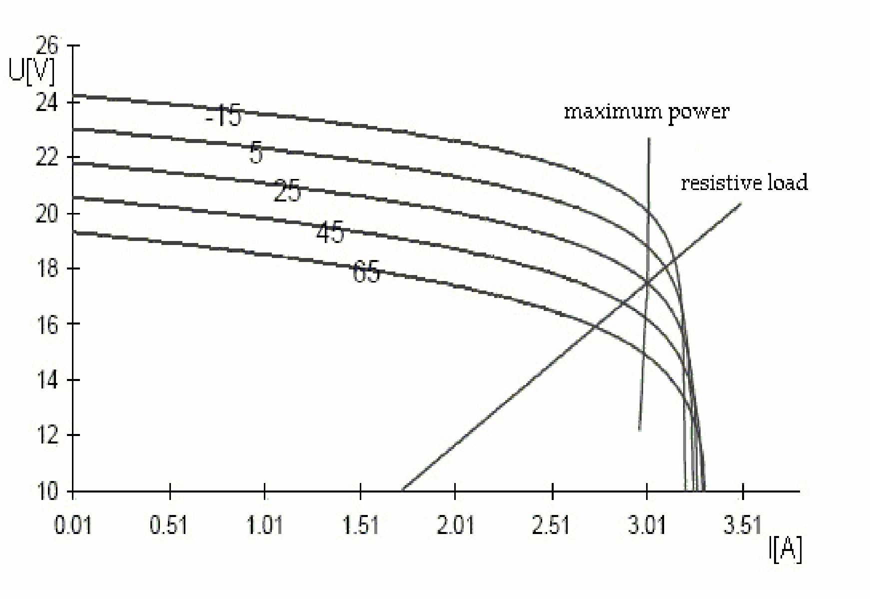

Figure 30: Influence of temperature change t^c [°C] on current and voltage of PV cell

When temperature of PV cell goes up then open circuit voltage goes down linearly and short circuit current go up.

5.1.2 Equation describing a behavior of PV cell

a) Equation for computation of PV cell current I^C depending on impress voltage U^C.

(it describes waveform of volt-ampere characteristic):

$$I^C = I^C_{SC}\left[1 - \exp\left(V^C - V^C_{0C} / V^C_t m\right)\right] \quad \text{[A]}$$

b) Computation of short circuit current depending on impinging radiation G_a and temperature of cell T^C:

$$I^C_{SC} = C1 * Ga + k1 * \left(T^C - T^C_0\right) \qquad \text{[A]}$$

$$T^C_0 = 273{,}15 + t^C_0 = 295{,}15 \text{ [K]}$$

c) Computation of open circuit voltage depending on impinging radiation G_a and temperature of cell T^C:

$$V^C_{0C} = V^C_{0C,0} + C3\left(T^C - T^C_0\right) - \exp\left(\frac{G_a - G_{aO}}{K3}\right) / K4 \qquad \text{[V]}$$

d) Computation of cell temperature depending on ambient temperature and impinging radiation G_a:

$$T^C = t_a + 273{,}15 + C2 * Ga \quad \text{[K]}$$

Impinging radiation G_a gives a rise to a heating effect of PV cell.

e) Computation of so called the thermal voltage depending on temperature of cell:

$$U^C_t = k * T^C / e \quad \text{[V]}$$

Influence of increasing temperature T^C increases also voltage U_t^C and it means decrease of volt-ampere characteristic flexion of PV cell and also its efficiency (smaller maximum power P^C_m). Decrease of volt-ampere characteristic causes resistance R_S.

Constant m in fraction denominator of exponential function for computation I^C_{SC} is the idealizing factor whose size influences flexion of volt-ampere characteristic. In model we choose such m as the flexion of volt-ampere characteristics gets near to reality.

Constant k = $1{,}381*10^{-23}$ [J/K] is the Boltzmann´s constant.

Constant e = $1{,}602*10^{-19}$ [C] is the elementary electric charge

Constants C_1, C_2, C_3, K_3, K_4 are specific parameters of PV cell

5.2 Application of PV cell model in computer program Swing

5.2.1 Controlix

The Controlix editor enables sequential relations combining logic and analog signals to be programmed graphically.

input ⇒ processing ⇒ outputs

Controlix enables the control logic of a process to be simulated and any type of mathematical or physical equation, logic and analog relations between variables and objects to be programmed. It also enables action on a page content and creation of animation effects.

A Controlix object has a series of “global” variables connected to the circuit. These variables can be used or repositioned directly by processing functions internal to the Controlix circuit object. In a circuit, Controlix can use several types of variables: integers, real numbers (single or double) and texts. Controlix is very well suited for complicated calculations with variables. It enables long calculations to be performed by subdividing them into simple elements. This editor provides you with the classic operators (addition, subtraction, multiplication and division) and also trigonometric functions (on polynomials, powers ...).

5.2.2 Application in Swing

In program Swing – Controlix was made the model of PV array. It is shown in Figure 31.

In this model are applied equations which are described above. For this model is possible to change passive input parameters like surface of one PV cell, number of cells in series and number of parallel cells of PV module, number of PV modules in series or parallel in one photovoltaic array and also open-circuit voltage of one module. The open-circuit voltage we can look for in producer catalogue. If we don’t change default variables in variable entries on main screen, the simulation will use these default parameters for the PV system in Pilsen:

Surface of one cell [m^2]	0,0105
Number of cells in series of PV module [-]	72
Number of parallel cells of PV module [-]	1
Number of PV modules in series [-]	8
Number of parallel PV modules [-]	3
Open-circuit voltage of module [V]	43,2

All these parameters we can look for in respective catalogue of PV module producers.

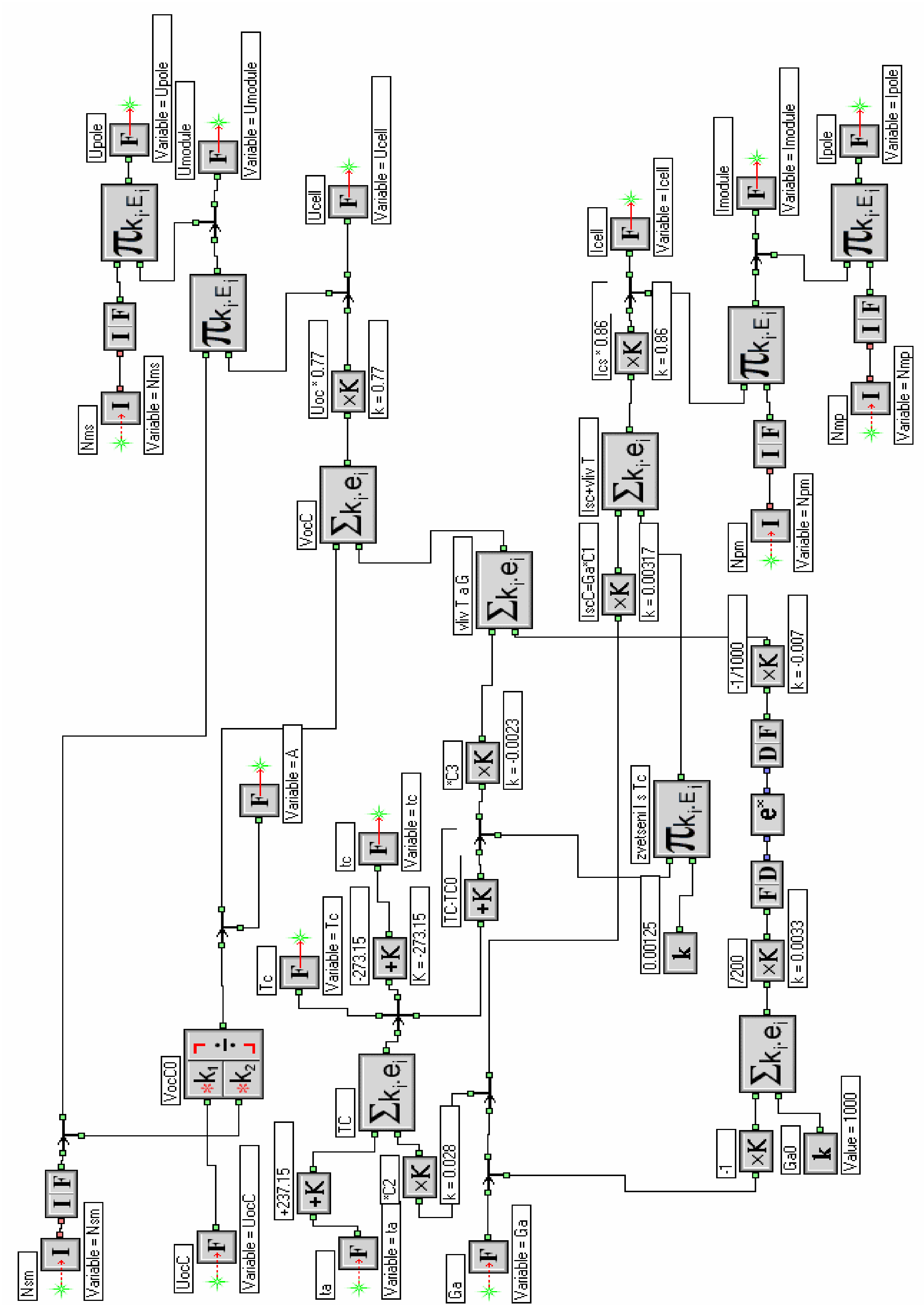

Figure 31: Model of photovoltaic array in Controlix

How we can see this mathematical model is possible to use almost for all PV modules different types with different numbers of cell, surface and open-circuit voltage.

When the simulation is working we can change values of impinging irradiance and ambient temperature. We have 2 possibilities how to change them. The first is to write new value into variable entry the same way like passive parameters and the second one is to put a mouse cursor in mouse-sensitive zone. For impinging irradiance G [W/m^2] there are two sensitive zones – one increases and second one decreases the value of impinging irradiance. It is the same for ambient temperature t [°C]. Both values are possible to change fluently during working process.

From actual input parameters are computed output values of current, voltage and power of one PV cell, PV module and whole PV array. Next two output values are temperature of cell and efficiency. All these parameters depend on impressed voltage on PV cell terminal. It is possible to see it in Figure 24 – in the working point A in the flexion of volt-ampere characteristic where is maximum efficiency. In most of cases of PV systems are use controlled power inverters which make voltage U_m almost constant automatically. This fact is used in mathematical model and I suppose that voltage is constant.

In Figure 32 we can see the main screen of simulation program. On upper part of screen we can change the input parameters and see the actual output parameters such as current, voltage and power of cell, module and array, also efficiency and temperature of cell. On button of screen are 6 graphs of most important values like impinging irradiance, current and voltage and power of whole PV array, efficiency and temperature of cell. That means we can analyse them digestedly. Time axis scale and all scales of value axes of all graphs are possible to change how we need.

In Figure 33 is a detail of first graph for impinging irradiation. The graph has 8 parts. The first four ones are for temperature of 0°C and rest of them for temperature of 20°C. For each value of temperature were changed values of impinging irradiation – 200, 400, 700, 1000 W/m^2. This is great for comparison of influence on array current, array voltage, array power, temperature of cell and so on. In Figure 32 the results are shown. How we can see current almost doesn’t depend on ambient temperature. For each the same irradiance and different temperature the current is almost the same. It is different for voltage. The value of voltage for same temperature 0°C is lower for impinging irradiance of 1000 W/m^2 than for 700 W/m^2. We can notice that voltage for values of 400 W/m^2 and 1000 W/m^2 are very similar. The values of array power are lower for the same impinging irradiance and higher temperature. The voltage doesn’t change its range so much as current. Voltage is changed approximately in range of 9 % of voltage nominal value (25/275) but for current is notably higher. The difference of cell temperature for the same impinging irradiation is, in this case, almost always 20°C because constant C_2 in equation for computation of cell temperature is too small and it means constant C_2 doesn't so big influence on it. The main factor is ambient temperature.

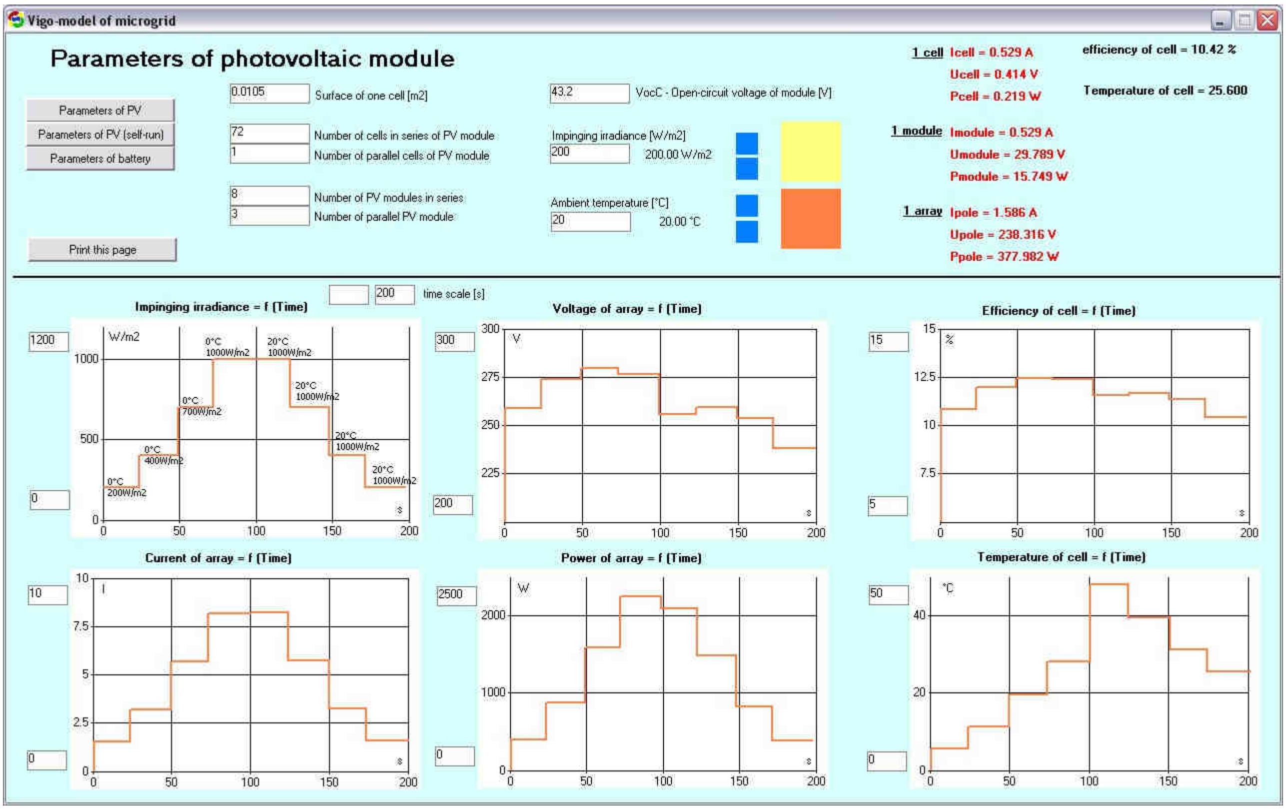

Figure 32: Impinging irradiance G_a and ambient temperature T are changed always in period of time

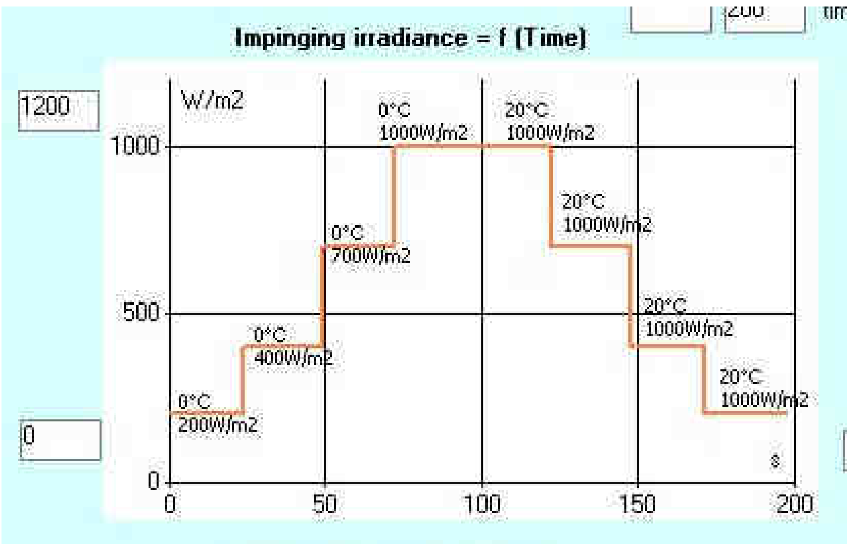

Figure 33: Detail of impinging irradiance graph in Figure 32

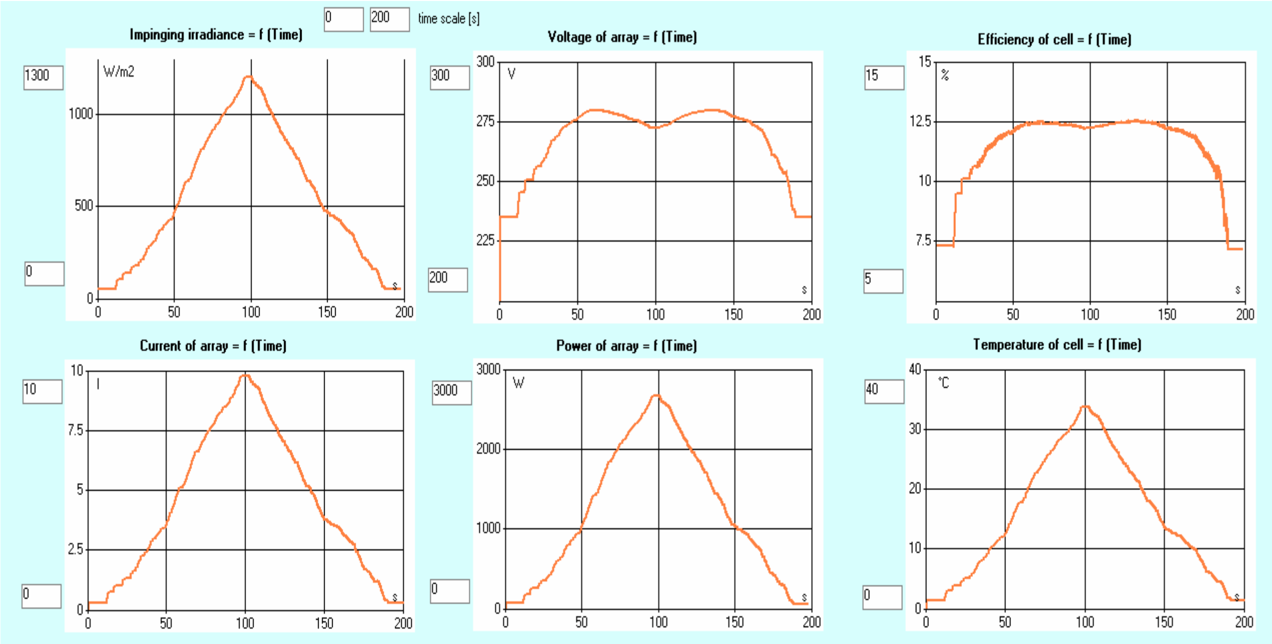

Figure 34: Impinging irradiance G_a is changing 50-1200-50 W/m^2 and ambient temperature t=0°C

In Figure 34 is shown dependence on impinging irradiation. The impinging irradiation was changed between 50 W/m^2 and 1200 W/m^2 during first 100 seconds and in the second part of graph was declined value of impinging irradiation from 1200 W/m^2 to 50 W/m^2. That was done for constant temperature 0°C in the Figure 34 and for temperature of 20°C in Figure 35.

In both cases the impinging irradiation was changed almost constantly whole time. Graphs of current and power of PV array and temperature have approximately the same shape. The shapes of graphs of array voltage and efficiency are different from other ones. If we compare Figure 34 and Figure 35 we can say that temperature influences quite a lot voltage of array and efficiency of PV system. Maximum voltage in both cases is about impinging irradiance of 750-800 W/m^2.

For values of irradiation between 0 and 500 W/m^2 voltage and efficiency grow up quite fast. Between 500 and 750 indeed grow up but not so fast and slope of curve is lower and lower when irradiation is growing up. If the value of impinging irradiation is higher than maximum for given temperature, the voltage starts to decline. More or less it is the same for efficiency of cell as well.

The maximum voltage for temperature 0°C is about 280 V and for 20°C it is only about 260 V. If we compare both graphs of voltage of array we can see that with higher temperature are values of voltage lower. On ambient temperature also depends on efficiency. For the temperature of 0°C is maximum efficiency about 12,5 % but for the temperature of 20°C is lower and maximum value of efficiency is about 11,5%.

If we compare diagrams of current, we can see that the influence of ambient temperature is almost zero and the currents are in both cases almost the same. That means that immediate values of power are similar. More examples you can also find in appendix.

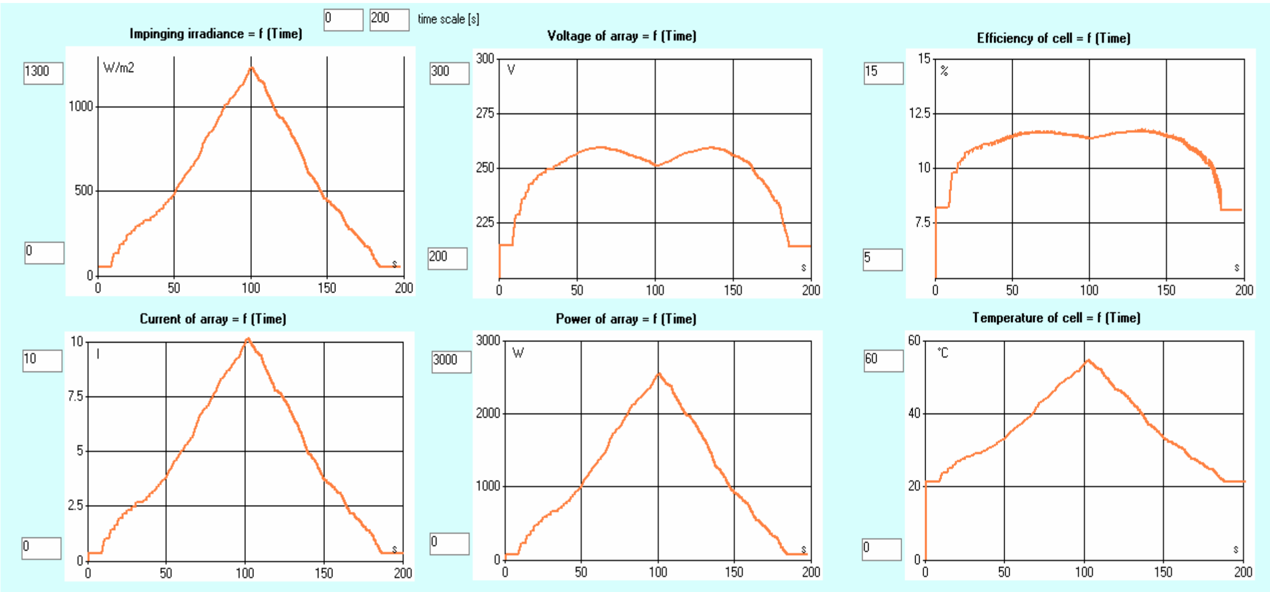

Figure 35: Impinging irradiance G_a is changing 50-1200-50 W/m^2 and ambient temperature t=20°C

5.2.3 Results from Controlix for various parameters

In this article I made 4 measurements for different ambient temperatures of -5°C, 10°C, 25°C and 40°C. During these measurements, the global impinging irradiance was changed by step value of 50 W/m^2. From results it was made 4 graphs (Figure 36 - Figure 39) for different magnitudes of efficiency, array power, array current and array voltage for PV system on the roof of Faculty of Electrical Engineering in Pilsen with parameters for this system.

In Figure 36 we can see how the maximum point of efficiency curves is shifted. For ordinary conditions of weather (in this case only temperature) the maximum value of efficiency is within the range of 700 and 800 W/m^2. For lower temperature this value increases. In interval between maximum efficiency and the highest possible value of impinging irradiation efficiency declines but with not such a big slope. However, between 0 W/m^{2}and 400 W/m^2 efficiency is changed more. We also can say that efficiency of PV cell is almost constant between 400 W/m^2 and 1200 W/m^2.

In Figure 37 is possible to see that array power is on ambient temperature linearly dependent. The slope of the straight line declines with increasing ambient temperature. For ambient temperature of 10°C is the slope approximately 2,17m^2. It is clear when the ambient temperature is higher, the slope of curves is lower. For irradiance of 1000 W/m^2 (standard condition) and temperature difference 15°C the PV system produces 113 W more each hour for temperature of 10°C than for ambient temperature of 25°C.

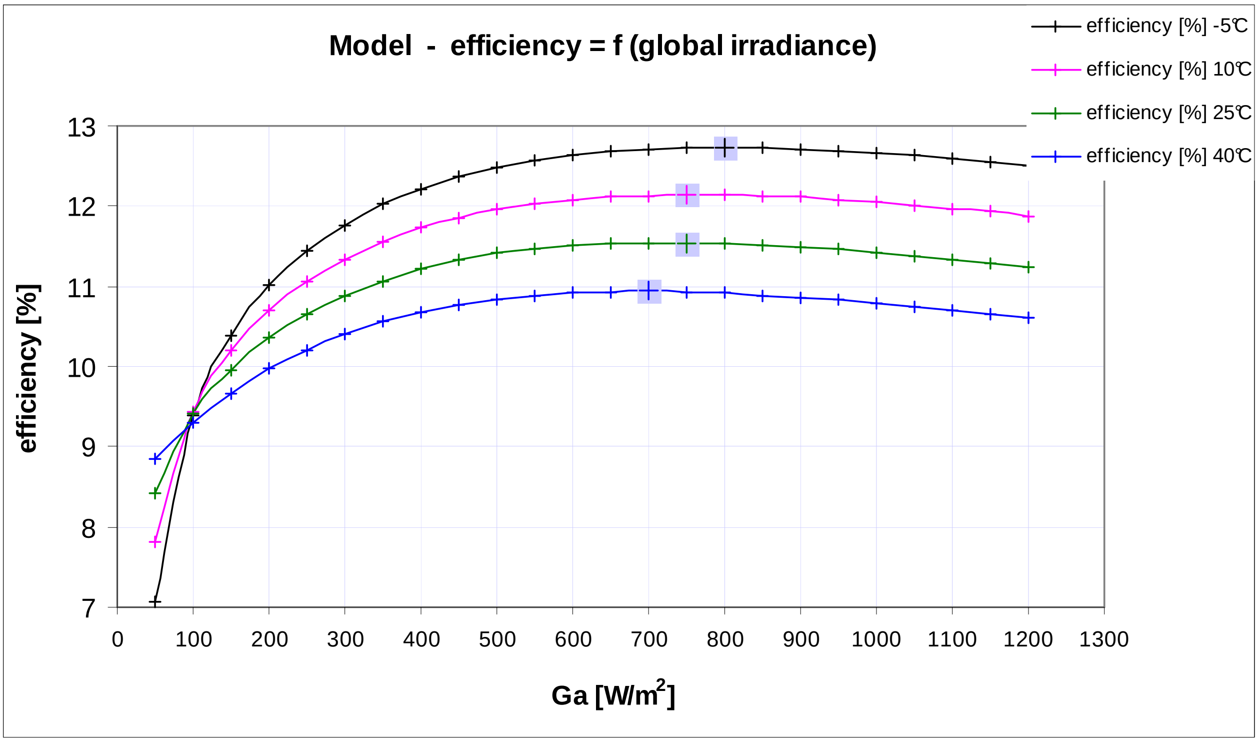

Figure 36: Simulated efficiency of PV dependent on global irradiance G_a for different temperatures

In Figure 38 is shown that current of PV cell doesn’t depend on ambient temperature. All current curves are almost the same. The differences are insignificant. The current is directly proportional impinging irradiation for all ordinary ambient temperatures.

In Figure 39 is voltage of PV array dependent on global irradiance G_a for different temperatures. The voltage goes in range from 200 V to 280 V. But for ordinary day the range of voltage is smaller. The temperature during day doesn’t change so much.

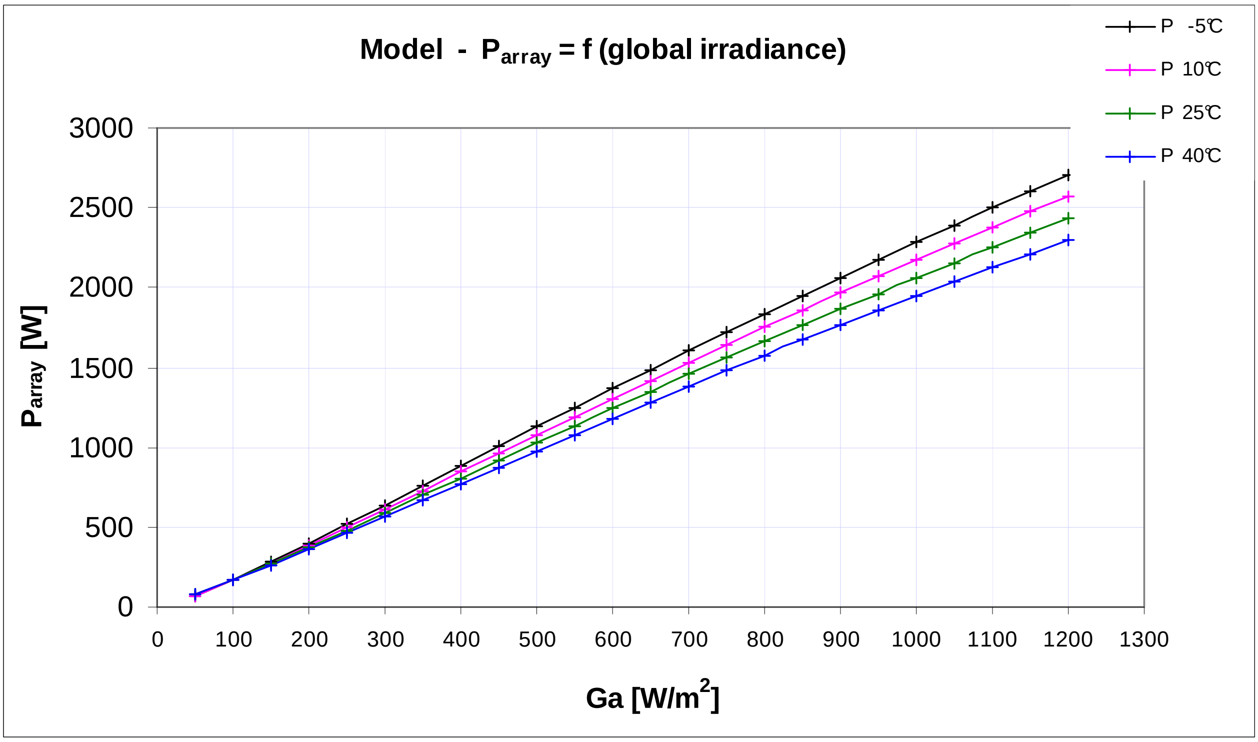

Figure 37: Power of PV array dependent on global irradiance G_a for different temperatures

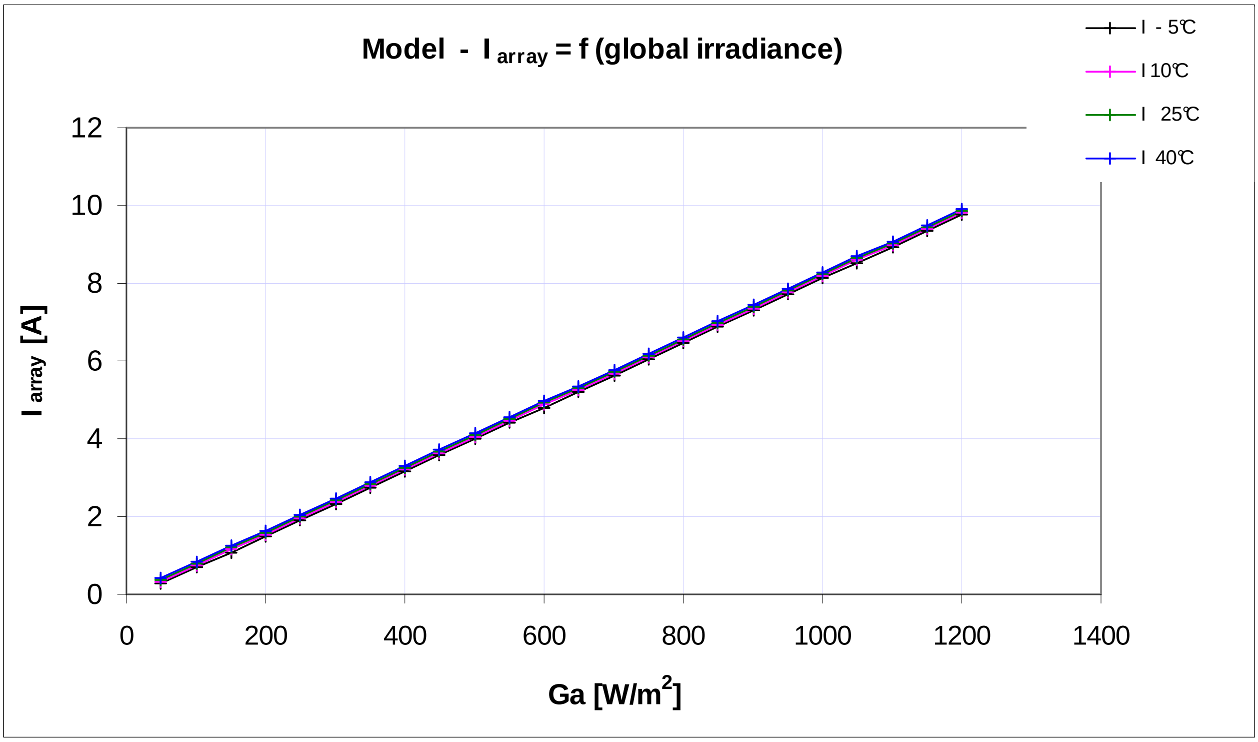

Figure 38: Current of PV array dependent on global irradiance G_a for different temperatures

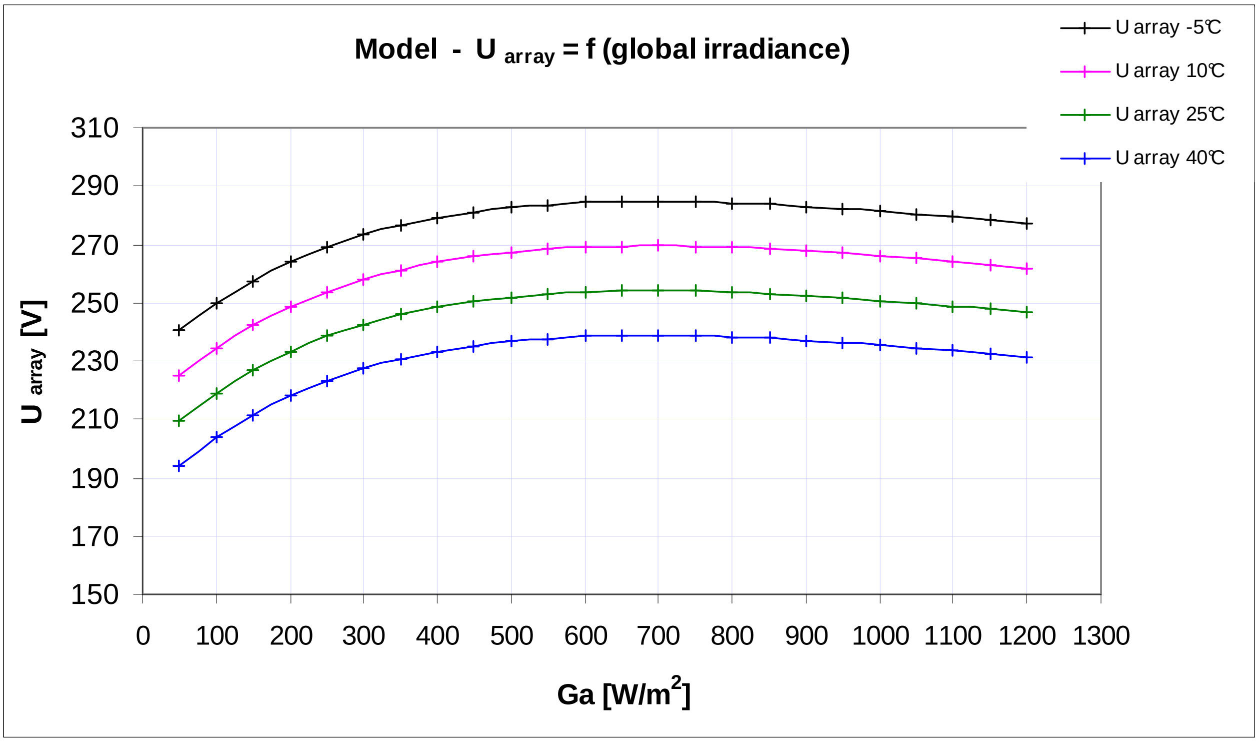

Figure 39: Voltage of PV array dependent on global irradiance G_a for different temperatures

6 COMPARISON OF PARAMETERS – MODEL AND REAL SYSTEM

In this article I compare real measured parameters of real photovoltaic system with values which were done by mathematical model in computer program Swing. This comparison is for PV array on the roof of Faculty of Electrical Engineering and I chose the measurement of one summer day 13.7.2008. According to the shape of global irradiance in Figure 40 we can estimate that the weather was partly cloudy whole day. Instantaneous values of irradiance were changed quite a lot in short periods of time during whole day.

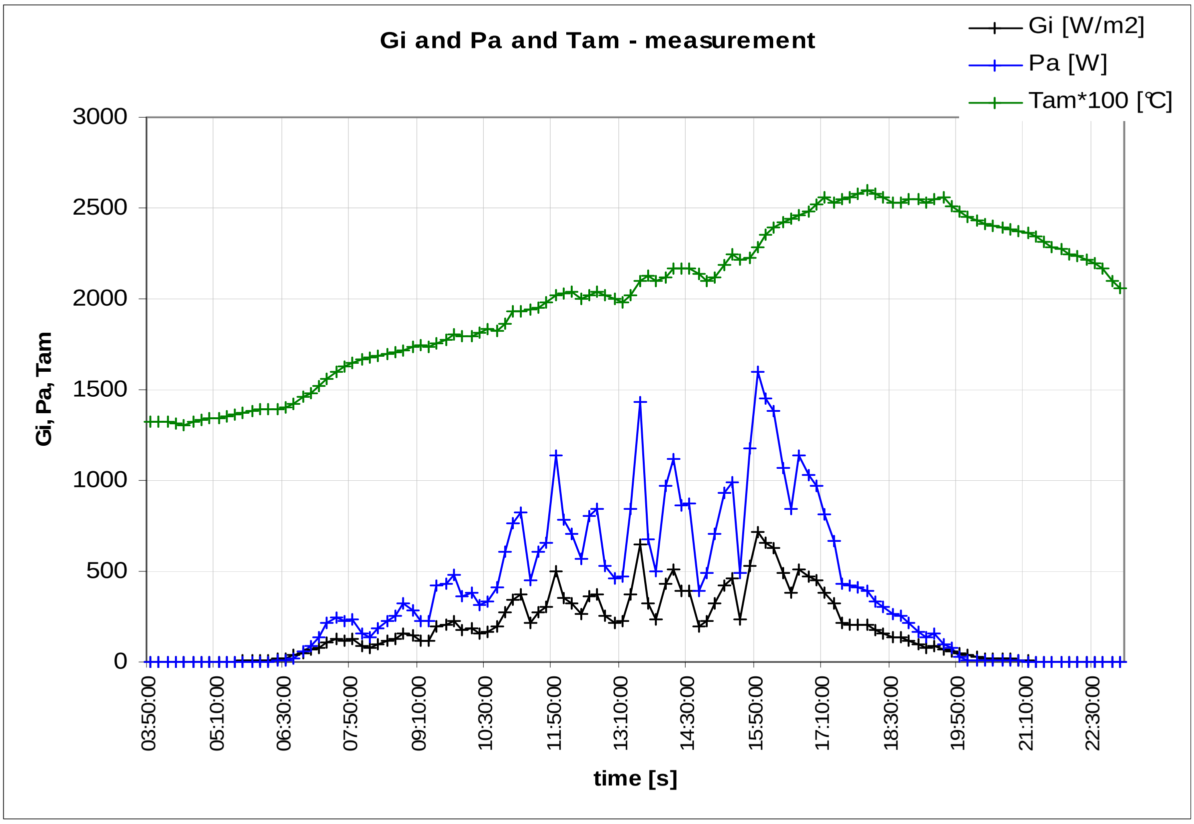

Figure 40: Dependence of PV array power on ambient temperature and impinging irradiance - 13.7.2007

In Figure 40 is shown dependence of PV array power on ambient temperature and impinging irradiance. Temperature was changed in range of 13°C and 26°C during whole day. The shape of power curve is, more or less, the same with the shape of global irradiance. Temperature doesn’t have such a big influence on power curve, how we can see. Temperature can change only instantaneous values of power in each instant of time but the shape of power curve will be the same like for global irradiance.

For graphs in Figure 41 - Figure 45 I put the real values of ambient temperature and impinging irradiation to simulation program of PV array in periods of time every 5 minutes and all output parameters were recorded. These output values were compared with measured values on PV array in next graphs like generator voltage, generator current and generator power.

In Figure 41 - Figure 43 we can see results. For power and current the graphs are almost the same. Differences between values are insignificant. For voltage are bigger differences between both values in the same time but not so much. The voltage of PV array model is without control of maximum power point tracking (MPPT). In Figure 44 we can notice real efficiency during whole day. Temperature of cell is in Figure 45. If we notice, ambient temperature was chanced during whole day in range of 13°C and temperature of cell in range of 29°C. Here we can clearly see influence of impinging irradiation on temperature of cell especially in the middle of curve in Figure 45. Between 10:00 and 18:00 several peaks are noticeable and their shape is very similar to global irradiance in Figure 40 in the same period of time.

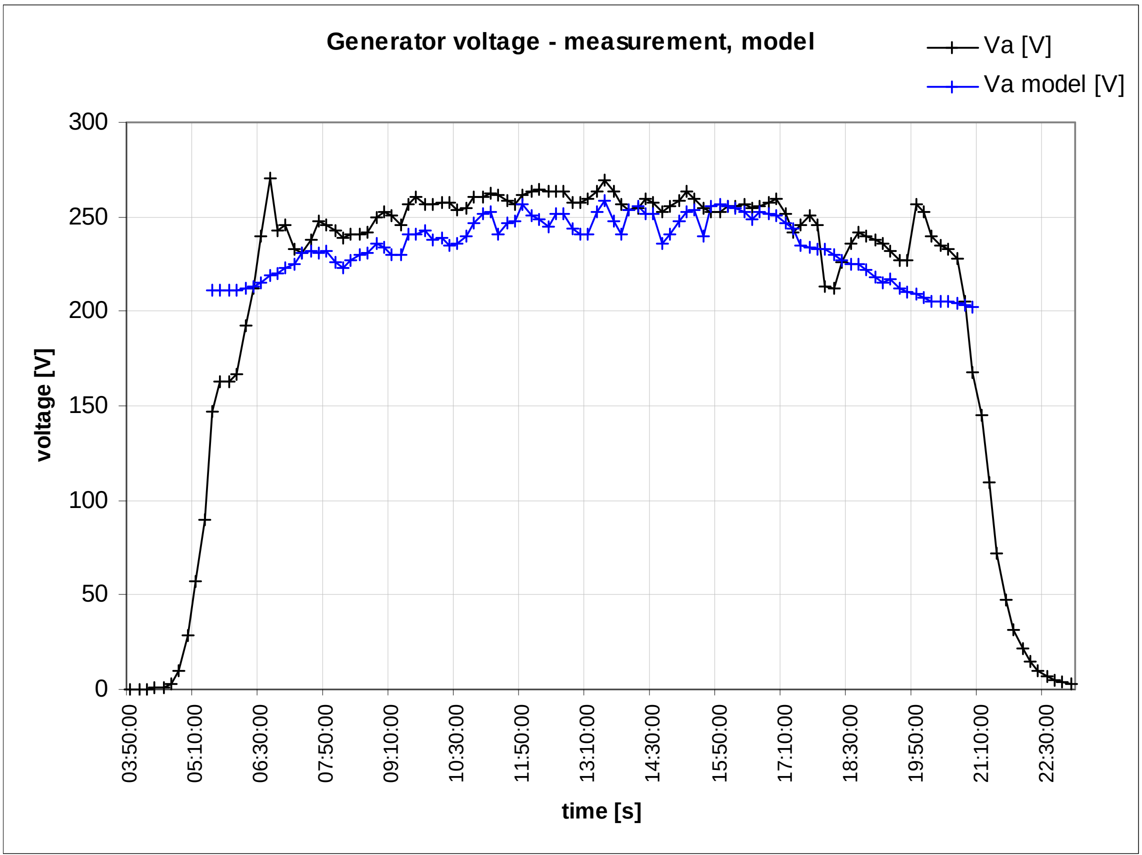

Figure 41: comparison of PV array voltages during a day – model and real system – 13.7.2008

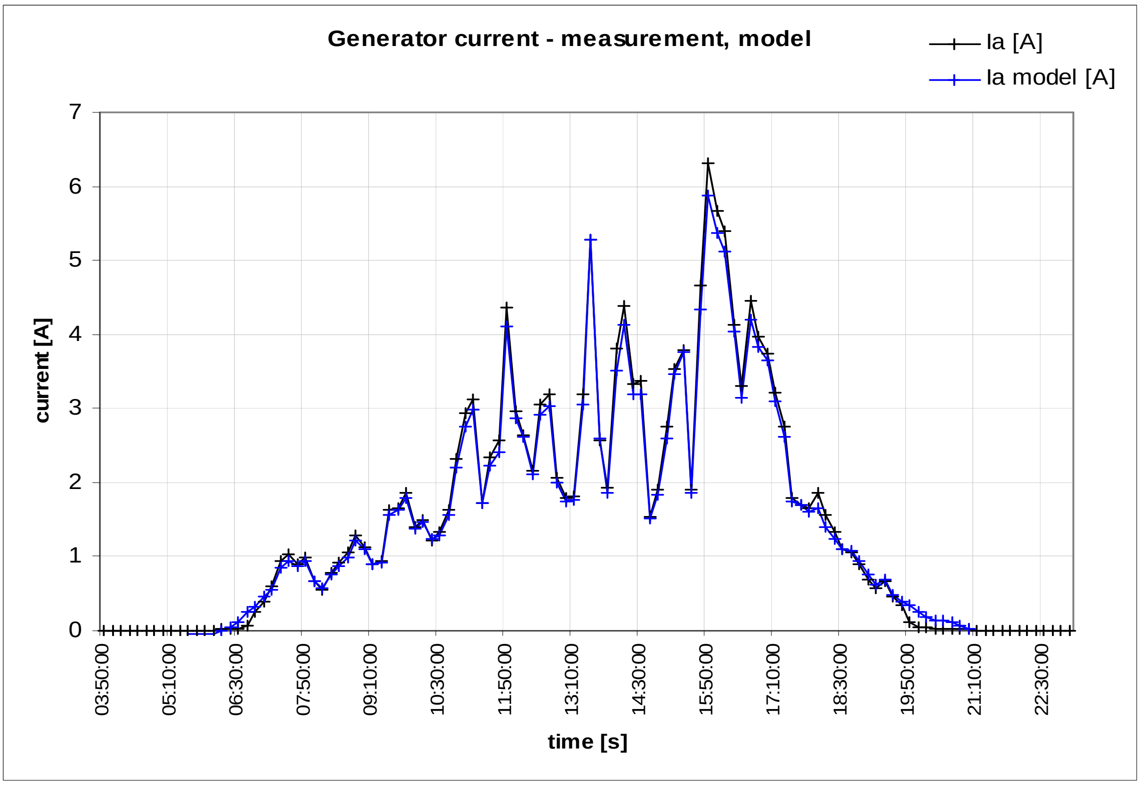

Figure 42: comparison of PV array currents during a day – model and real system – 13.7.2008

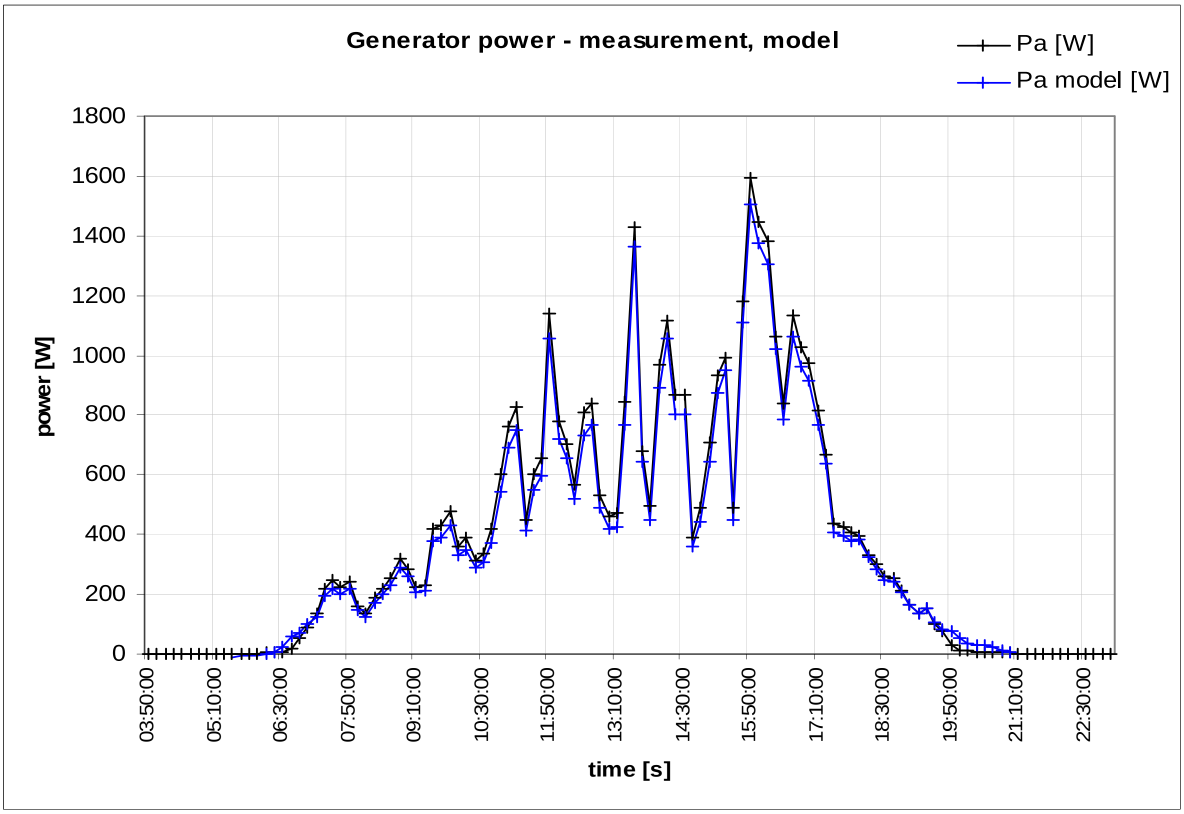

Figure 43: comparison of PV array powers during a day – model and real system – 13.7.2008

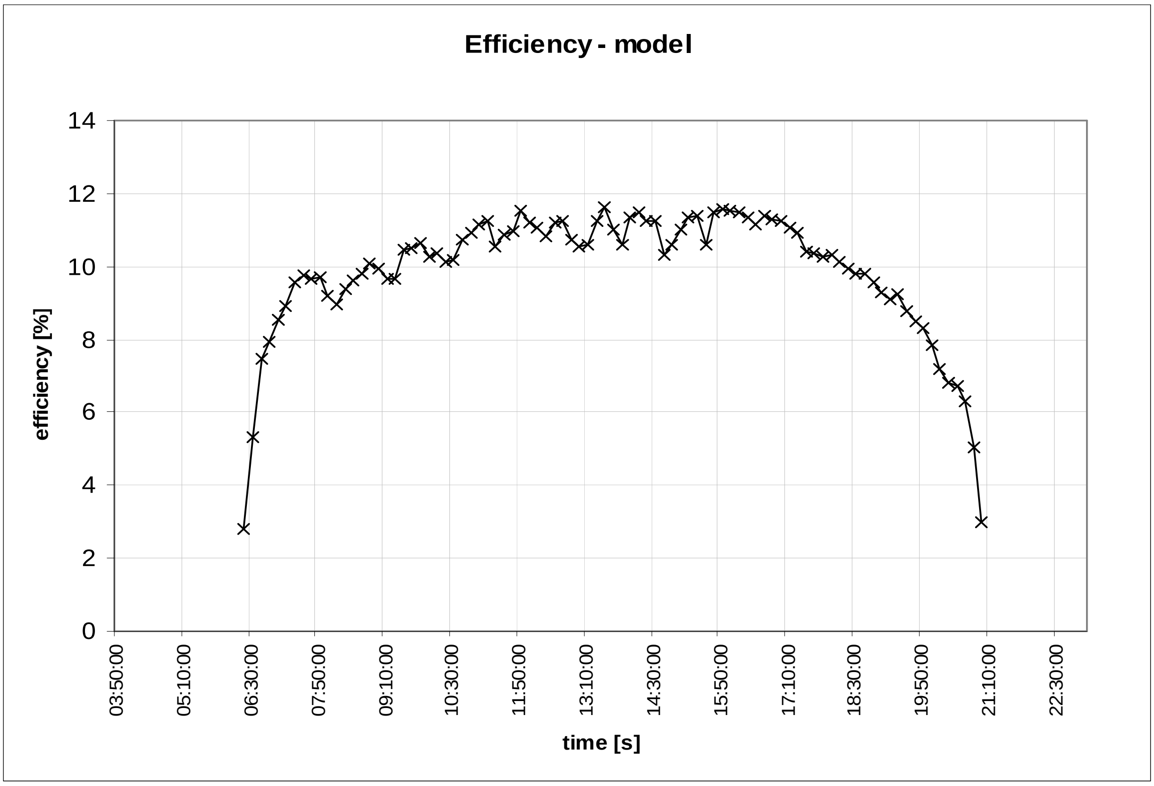

Figure 44: efficiency of PV array during a day – model Swing (Controlix) – 13.7.2008

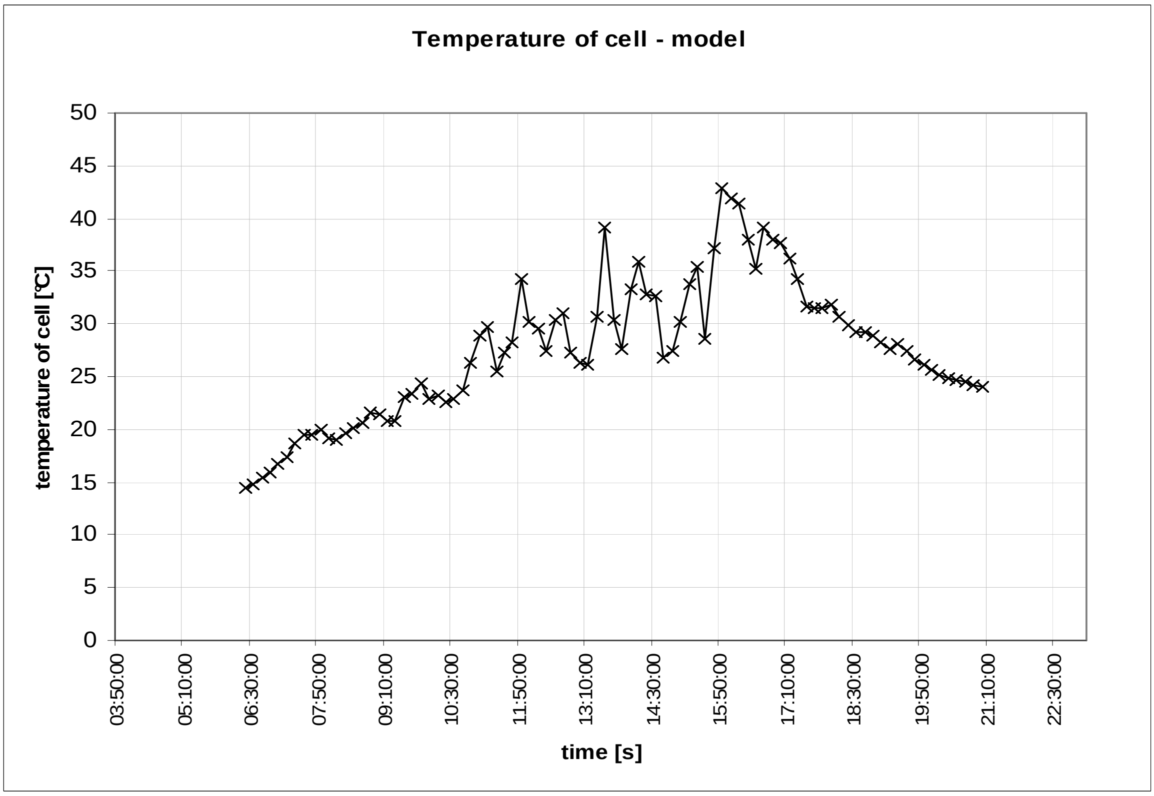

Figure 45: Temperature of PV cell during a day – model Swing (Controlix) – 13.7.2008

In this table are all values used for graphs in Figure 41 - Figure 45 for easier orientation.

time	Tam [℃]	Gi [W/m²]	Va [V]	Ia [A]	Pa [W]	Va model [V]	Ia model [A]	Pa model [W]	efficiency model [%]	TC model [℃]
06:20:00	13,96	14,79	211,77	0,03	6,27	213,108	0,035	7,479	2,79	14,374
06:30:00	14,06	23,04	239,66	0,03	7,22	214,923	0,104	22,273	5,33	14,705
06:40:00	14,24	41,76	270,63	0,06	15,05	218,878	0,259	56,691	7,48	15,409
06:50:00	14,56	49,5	243,17	0,25	55,56	220,18	0,324	71,348	7,94	15,946
07:00:00	14,84	64,8	245,82	0,39	89,18	222,977	0,451	100,665	8,56	16,654
07:10:00	15,17	77,41	233,08	0,59	137,43	225,051	0,557	125,307	8,92	17,337
07:20:00	15,55	112,26	230,57	0,95	218,28	230,758	0,847	195,341	9,59	18,694
07:30:00	15,95	124,76	237,75	1,03	245,22	232,341	0,951	220,996	9,76	19,444
07:40:00	16,23	116,25	247,71	0,9	222,71	230,712	0,882	203,439	9,64	19,486
07:50:00	16,47	123,2	245,24	0,98	240,19	231,561	0,94	217,579	9,73	19,92
08:00:00	16,7	89,84	242,93	0,66	160,73	225,755	0,665	150,017	9,2	19,216
08:10:00	16,79	77,67	238,68	0,56	133,21	223,447	0,564	126,062	8,95	18,965
08:20:00	16,84	100,21	240,5	0,77	185,98	227,42	0,751	170,708	9,39	19,646
08:30:00	16,93	115,23	241,05	0,92	221,06	229,82	0,875	201,082	9,62	20,156
08:40:00	17,05	129,49	241,54	1,05	254,48	230,454	0,994	231,942	9,81	20,676
08:50:00	17,19	156,51	250,03	1,28	319,33	235,709	1,217	286,927	10,1	21,572
09:00:00	17,37	143,34	252,14	1,13	283,79	233,666	1,109	259,072	9,96	21,382
09:10:00	17,46	118,7	250,61	0,89	223,88	229,841	0,906	208,144	9,66	20,784
09:20:00	17,37	119,96	245,62	0,93	229,48	230,139	0,916	210,821	9,68	20,73
09:30:00	17,51	198,14	256,33	1,63	419,01	240,636	1,562	375,949	10,46	23,057
09:40:00	17,71	204,95	260,44	1,66	431,06	241,221	1,62	390,781	10,51	23,45
09:50:00	18,07	224,72	256,26	1,87	480,13	242,984	1,784	433,502	10,63	24,362
10:00:00	17,97	176,01	256,48	1,41	361,72	237,486	1,381	327,981	10,27	22,898
10:10:00	17,95	186,39	257,79	1,5	387,23	238,798	1,467	350,314	10,36	23,169
10:20:00	18,18	158,37	257,36	1,22	314,47	234,958	1,236	290,455	10,11	22,615
10:30:00	18,29	165,1	253,22	1,32	334,51	235,746	1,292	304,574	10,17	22,913
10:40:00	18,22	197,09	254,91	1,63	416,36	239,796	1,556	373,202	10,74	23,739
10:50:00	18,6	274,69	260,17	2,32	603,58	247,115	2,199	543,462	10,9	26,292
11:00:00	19,31	341,97	260,58	2,93	763,94	251,24	2,758	692,923	11,17	28,886
11:10:00	19,36	368,47	262,86	3,13	823,32	252,712	2,977	752,4	11,25	29,678
11:20:00	19,41	217,27	261,69	1,72	450,86	240,837	1,727	415,975	10,55	25,494
11:30:00	19,54	277,66	258,99	2,34	604,83	246,405	2,227	548,761	10,89	27,316
11:40:00	19,83	300,39	256,63	2,57	655,71	247,891	2,416	598,831	10,99	28,241
11:50:00	20,18	504,87	261,62	4,36	1139,52	257,023	4,108	1055,803	11,53	34,317
12:00:00	20,28	354,26	263,05	2,97	780,72	250,982	2,863	718,525	11,18	30,2
12:10:00	20,37	325,05	264,77	2,65	701,08	249,08	2,622	653,009	11,07	29,473
12:20:00	20,04	263,64	263,12	2,15	566,45	244,695	2,112	516,816	10,81	27,421
12:30:00	20,2	361,33	263,85	3,06	806,32	251,461	2,92	734,385	11,2	30,316
12:40:00	20,43	375,34	263,01	3,2	840,95	251,98	3,037	765,258	11,24	30,938
12:50:00	20,19	250,79	257,19	2,06	531,72	243,385	2,007	488,408	10,73	27,212
13:00:00	20,01	218,95	257,55	1,79	461,36	240,325	1,743	418,996	10,54	26,222
13:10:00	19,84	222,88	259,73	1,81	469,94	240,991	1,775	427,735	10,58	26,081
13:20:00	20,18	376,89	263,6	3,19	842,59	252,318	3,049	769,419	11,25	30,733
13:30:00	20,95	647	269,18	5,28	1427,57	258,133	5,285	1364,313	11,62	39,066
13:40:00	21,32	320,73	263,52	2,57	679,24	247,815	2,588	641,437	11,02	30,3
13:50:00	21,02	233,46	256,8	1,93	495,51	240,871	1,866	449,551	10,61	27,558

14:00:00	21,13	432,14	253,92	3,8	967,72	253,813	3,509	890,609	11,36	33,229
14:10:00	21,71	506,41	254,25	4,38	1116,57	255,498	4,125	1053,969	11,47	35,889
14:20:00	21,68	394,6	259,76	3,33	864,79	251,659	3,201	805,46	11,25	32,729
14:30:00	21,69	392,63	257,92	3,38	869,36	251,554	3,184	800,973	11,24	32,683
14:40:00	21,34	192,17	252,84	1,54	389,27	236,037	1,526	360,164	10,33	26,722
14:50:00	20,97	229,19	255,1	1,91	488,45	240,489	1,831	440,247	10,59	27,388
15:00:00	21,19	322,53	258,25	2,75	709,46	248,069	2,603	645,683	11,03	30,22
15:10:00	21,9	426,32	263,31	3,53	932,38	252,803	3,463	875,566	11,32	33,836
15:20:00	22,43	461,59	259,11	3,78	990,67	253,521	3,757	952,487	11,37	35,355
15:30:00	22,12	233,14	255,06	1,91	487,13	239,709	1,867	447,44	10,58	28,647
15:40:00	22,27	531,79	252,95	4,67	1180,89	255,473	4,337	1107,988	11,48	37,16
15:50:00	22,84	717,69	252,58	6,31	1594,19	256,256	5,876	1505,768	11,56	42,936
16:00:00	23,5	657,03	255,46	5,67	1447,73	255,569	5,376	1373,997	11,53	41,896
16:10:00	23,91	625,03	255,77	5,4	1379,93	254,992	5,113	1303,761	11,5	41,41
16:20:00	24,19	494,51	256,51	4,14	1064,84	252,674	4,035	1019,477	11,36	38,036
16:30:00	24,38	387,17	254,13	3,3	840,85	248,55	3,148	782,466	11,14	35,222
16:40:00	24,65	514,66	255,3	4,45	1135,14	252,689	4,203	1062,121	11,37	39,062
16:50:00	24,8	468,65	257,55	3,98	1024,83	251,325	3,823	960,915	11,3	37,924
17:00:00	25,17	448,66	259,7	3,75	974,63	250,296	3,659	915,885	11,25	37,734
17:10:00	25,59	381,28	251,56	3,22	812,24	247,023	3,103	766,571	11,08	36,266
17:20:00	25,26	321,44	241,85	2,75	665,61	243,843	2,607	635,666	10,9	34,259
17:30:00	25,52	216,8	245,3	1,78	436,01	234,551	1,743	408,77	10,39	31,59
17:40:00	25,61	210,7	250,79	1,7	425,69	233,797	1,693	395,73	10,35	31,51
17:50:00	25,78	201,61	245,29	1,66	407,53	232,603	1,618	376,334	10,29	31,425
18:00:00	25,99	205,91	213,26	1,85	394,7	232,876	1,654	385,213	10,31	31,755
18:10:00	25,75	176,1	211,89	1,57	332,5	229,502	1,407	322,988	10,11	30,681
18:20:00	25,55	155,38	226,06	1,33	299,21	227,029	1,235	280,418	9,95	29,901
18:30:00	25,29	138,21	236,25	1,1	260,61	224,842	1,092	245,55	9,79	29,16
18:40:00	25,32	136,54	241,29	1,05	253,72	224,56	1,078	242,107	9,78	29,142
18:50:00	25,48	119,1	240,27	0,89	213,34	221,723	0,935	207,262	9,59	28,815
19:00:00	25,52	96,58	238,23	0,69	165,06	217,942	0,749	163,171	9,31	28,224
19:10:00	25,3	81,86	235,5	0,57	134,46	215,541	0,626	134,984	9,09	27,592
19:20:00	25,48	90,52	232,05	0,67	156,23	216,92	0,698	151,507	9,22	28,015
19:30:00	25,57	65,45	227,21	0,45	101,51	212,159	0,491	104,263	8,78	27,403
19:40:00	25,14	54,4	226,61	0,34	78	210,394	0,399	83,88	8,5	26,663
19:50:00	24,81	49,19	256,93	0,12	27,44	209,66	0,355	74,332	8,33	26,187
20:00:00	24,53	37,22	252,69	0,05	12,59	207,404	0,255	52,816	7,82	25,572
20:10:00	24,29	28,27	239,6	0,04	9,02	205,673	0,18	36,995	7,21	25,082
20:20:00	24,15	24,36	234,43	0,03	6,54	204,932	0,147	30,143	6,82	24,832
20:30:00	24,04	23,7	233,03	0,03	6,28	204,893	0,141	28,947	6,73	24,704
20:40:00	23,9	20,6	227,57	0,03	5,88	204,324	0,115	23,536	6,3	24,477
20:50:00	23,84	14,78	204,88	0,03	5,36	203,027	0,067	13,577	5,06	24,254
21:00:00	23,76	9,92	167,97	0,03	5,25	201,951	0,026	5,337	2,97	24,038

7 CONCLUSION

The aim of this work was to provide insight into modelling and simulation of a PV system. This model is possible to use for different types of PV array, the mathematical model (created in PC program Swing - Controlix) is possible to use for several types of PV cells and several wirings. I allowed for only 2 main input parameters – impinging irradiation and ambient temperature. It is also possible to change passive parameters of PV array. Other, like influence of wind (blow of wind), were omitted because of random action and it is very difficult to predict it.

The validation of this mathematical model was performed through the comparison between the simulation results and the measurements of real PV system on the roof of Faculty of Electrical Engineering.

From graphs we can also persuade behaviour of different types of PV cells (PV arrays). Basic physical rules of different PV cells are, more or less, similar. Only shapes of curves could be a little bit different and shifted.

This mathematical model of PV cells is possible to use with combination with other mathematical models of parts of microgrid (battery, fuel cell, regulator, etc.) and simulate whole system like a island operation or interconnection to electrical network.

If we know approximately an average value of impinging irradiation where we want to design a new PV system and a exact type of PV modules, we will be able to say how much electricity the PV system will generate a year. That means we can estimate economic return of vested capital to buying of PV system.

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http://www.pvresources.com/en/solarcells.php
http://www.ee.washington.edu/research/sesame/publication/Conference/2007/Campbell_PWL_PV_Model_NAPS2007.pdf
http://alumni.media.mit.edu/~nate/AES/PV_Theory_II.pdf
http://books.google.com/books?id=tNelPKdQxoMC&pg=PA137&ots=W8nKcEfgSh&dq=parameters+of+solar+cell+-+open+circuit+voltage,+short+circuit+current&ei=WalKR_WWB4nE6wKm38j5Bg&sig=--kcKd1nvVAw5OIGePHtO_Xn4LA#PPA137,M1
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http://books.google.com/books?q=parameters+of+solar+cell+-+open+circuit+voltage,+short+circuit+current&ots=5-BDAUkbpJ&sa=X&oi=print&ct=title&cad=legacy
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http://ieeexplore.ieee.org/iel3/4263/12206/00564054.pdf?arnumber=564054
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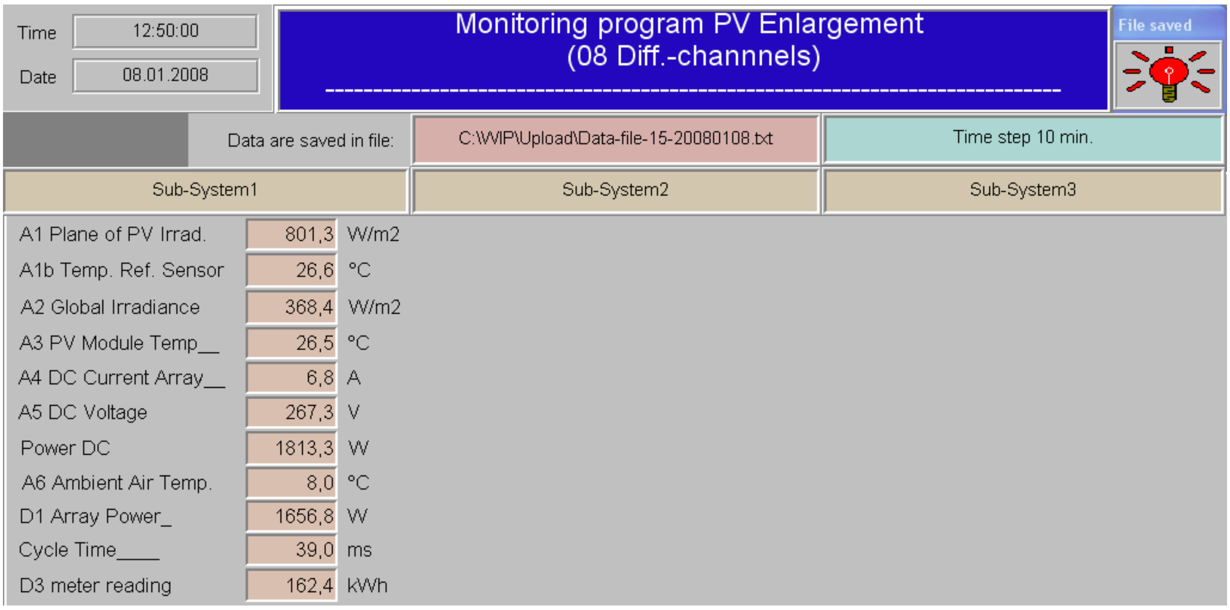
9 LIST OF FIGURES

10 APPENDIXS

10.1 Appendix A



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3; 1862,48; 1771,48; 1504,84;
4; 141,36;
5; 39,00;

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1; 400,11; 370,42; 185,73; 8,02; 7,91; 7,82;
2; 863,62; 777,34; 249,63; 30,48; 28,67; 26,47; 28,49; 27,73; 26,55; 334,80; 270,66; 201,53; 8,15; 6,71; 0,03; 2011,35; 1816,58; 10,63;
3; 1824,50; 1648,75; -4,81;
4; 162,36;
5; 38,00;

0; 15; 13:00:00; 08.01.2008; 1GC20;
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2; 849,54; 594,95; 236,36; 27,58; 23,56; 17,68; 27,02; 24,76; 20,54; 281,64; 265,09; 248,17; 7,62; 5,26; 1,98; 1983,80; 1401,69; 524,40;
3; 1811,84; 1277,87; 464,65;
4; 177,36;
5; 39,00;

PV Enlargement: File format for PE Monitoring Data

0; SysID; Time; Date; Comment;
1; Gh-h; Gh; Gh-l; Tam-h; Tam; Tam-l; Ws-h; Ws; Wd;
2; Gi-h; Gi; Gi-l; Tref-h; Tref; Tref-l; Ta-h; Ta; Ta-l; Va-h; Va; Va-l; Ia-h; Ia; Ia-l; Pa-h; Pa; Pa-l;
3; Pio-h; Pio; Pio-l;
4; Ptu;
5; C-time;

Annex:

0 Integer # Line Number (=0)

	SysID	Word	System Identification Number
	Time	hh:mm:ss	Time of Recording
	Date	dd/mm/yyyy	Date of Recording
	Comment String		System Identification Name e.g. 3GC10 (3 Sub-systems, Grid Connected, Installed Power 10kWp)

1 Integer # Line Number (=1)

	Gh-h	W/m2	Total Irradiation on Horizontal Plane Maximum
A2 Sensor2	Gh	W/m2	Total Irradiation on Horizontal Plane
	Gh-l	W/m2	Total Irradiation on Horizontal Plane Minimum
	Tam-h	°C	Ambient Temperature in the Shade Maximum
A6 Sensor6	Tam	°C	Ambient Temperature in the Shade
	Tam-l	°C	Ambient Temperature in the Shade Minimum
	Ws-h	m/s	Wind Speed Maximum
	Ws	m/s	Wind Speed
	Wd	deg	Wind Direction (N=0, S=180)

2 Integer # Line Number (=2)

	Gi-h	W/m2	PV Generator Array Plane Irradiation Maximum;
A1a Sensor0	Gi	W/m2	PV Generator Array Plane Irradiation
	Gi-l	W/m2	PV Generator Array Plane Irradiation Minimum
	Tref-h	°C	Reference Sensor Temperature Maximum
A1b Sensor1	Tref	°C	Reference Sensor Temperature
	Tref-l	°C	Reference Sensor Temperature Minimum
	Ta-h	°C	PV Generator Cell Temperature Maximum
A3 Sensor3	Ta	°C	PV Generator Cell Temperature
	Ta-l	°C	PV Generator Cell Temperature Minimum
	Va-h	V	PV Generator Voltage Maximum
A5 Sensor5	Va	V	PV Generator Voltage
	Va-l	V	PV Generator Voltage Minimum
	Ia-h	A	PV Generator Current Maximum
A4 Sensor 4	Ia	A	PV Generator Current
	Ia-l	A	PV Generator Current Minimum
	Pa-h	kW	PV Generator Power Maximum
Calculated	Pa	kW	PV Generator Power
	Pa-l	kW	PV Generator Power Minimum

3 Integer # Line Number (=3)

	Pio-h	kW	Inverter AC Power Out Maximum
D1 Sensor7	Pio	kW	Inverter AC Power Out
	Pio-l	kW	Inverter AC Power Out Minimum

4 Integer # Line Number (=4)

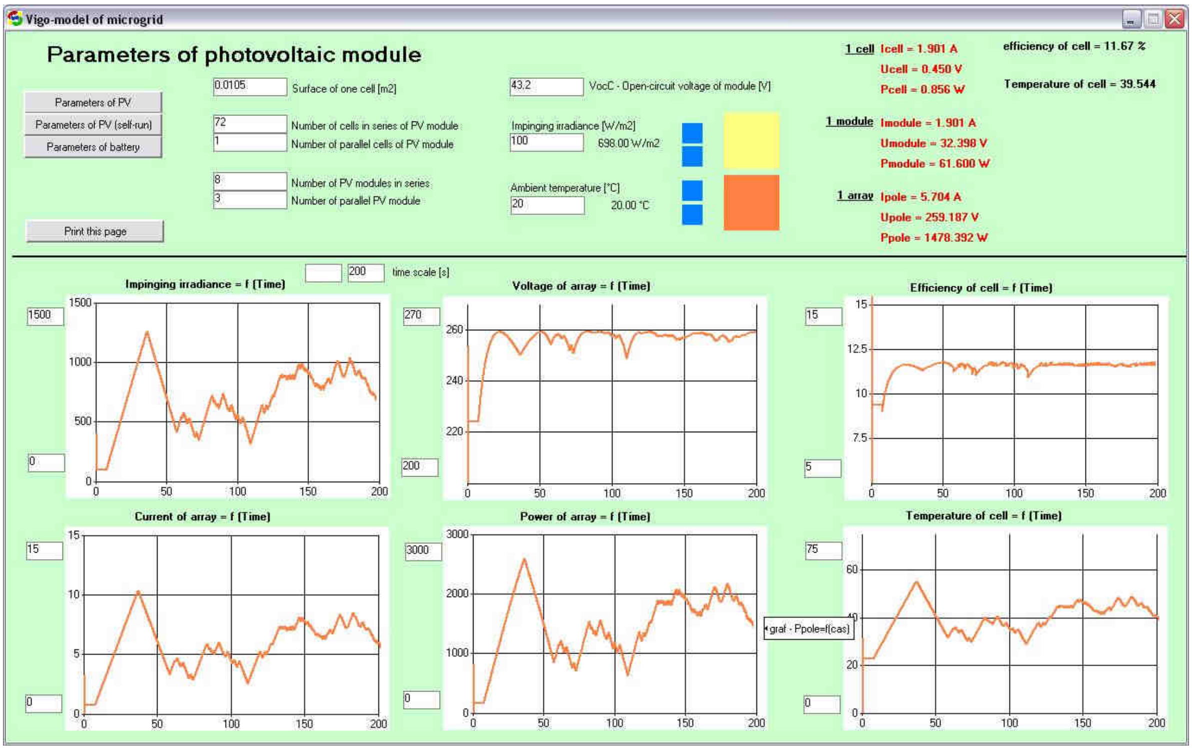
D3 Sensor8	Ptu	kWh	AC Energy to Utility Grid

5 Integer # Line Number (=5)

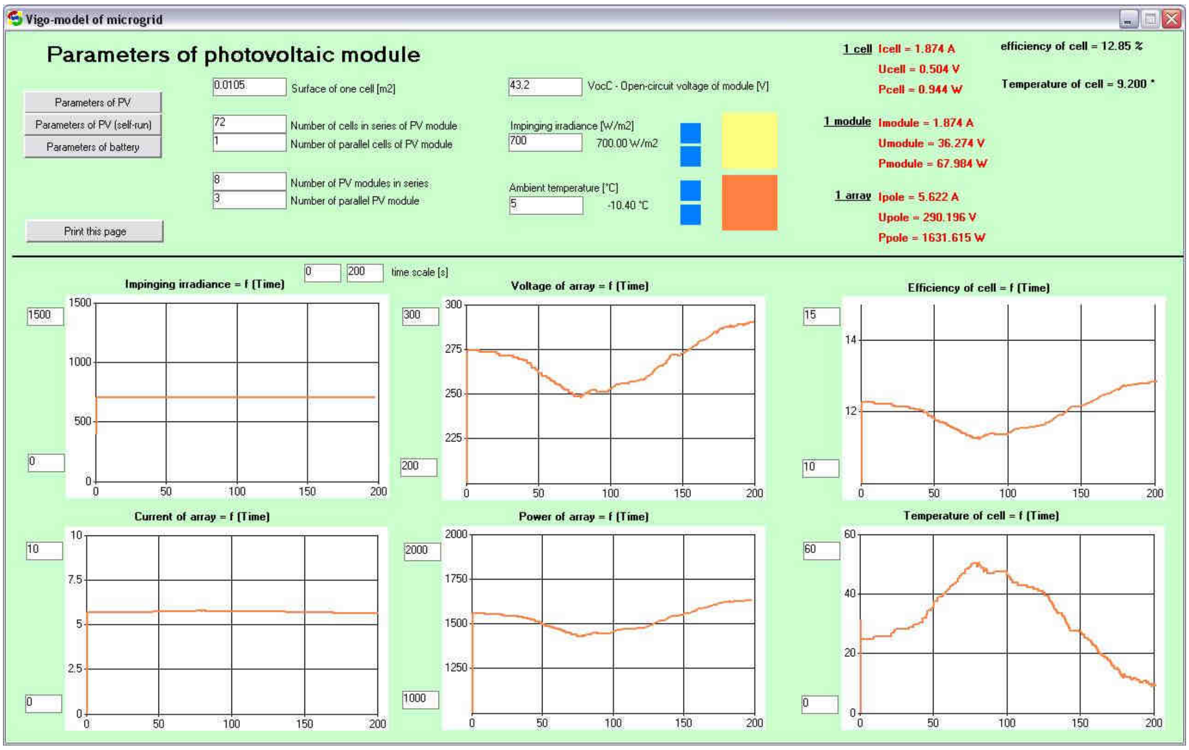
Cycle time	C-time	ms	Time which is required to read-out all values

10.2 Appendix B

Random change of impinging irradiation and constant ambient temperature of 20°C



Random not too fast change of ambient temperature and constant impinging irradiation of 700 W/m^2



10.3 Appendix C

Month summation of luminous exposure [h] – location: Plzeň (Mikulka), measured by gauging station Mikulka, elevation above sea-level - 360 m (Měsíční součty slunečního svitu v hodinách)

Year	Jan	Feb	Mar	May	Apr	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2004							245,4	221,2	193,5	119,4	38,4	29,1
2005	58,2	86,8	145,1	184,7	256,6	246,2	210	180,1	197,8	168	35	24,2
2006	70,5	81,3	102,4	153,3	220	264,4	336,5	133,7	251,9	123,3	49,6	53,7
2007	45,5	66,4	152,7	298,2								