Design and application of autonomous data acquisition systems used as calibration and qualification tool in photovoltaics

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In the paper basic design rules and possible applications of specialised autonomous data acquisition systems (DAS) in photovolatics (PV) are discussed. Their usefulness for both estimation of PV modules rating and prediction of the overall PV system actual performance, especially at strongly changeable weather and low insolation conditions, is presented. Some technical guidelines how to measure solar irradiation and current-voltage (I-V) curves of PV modules and big PV arrays are given. Examples of analysis and presentation of data stored by several installed systems are shown. Finally, new concept of modular PV DASs developed in Solar Lab which allows to reduce cost of installation yet increasing flexibility and extendibility of the PV monitoring systems is described. The concept is based on fully self-contained functional PVDA-Modules (PV Data Acquisition Modules). The heart of PVDA-Module is an 8-bit PIC family microcontroller (RISC-type). Each module is uniquely addressed and it communicates with PC computer, i.e., receives commands and/or exports stored data via RS485 bus with baud rate up to 100 kB and distance up to 1.2 km. Several examples of PVDA-Modules are given. A substantial list of representative references may be helpful for those who are going to get involved in photovoltaic measurement and monitoring.

Keywords: data acquisition system, photovoltaics, PV modules.

1. Introduction – what is the purpose of using PV data acquisition systems?

Specialised photovoltaic (PV) data acquisition systems (DAS) (or PV Monitoring Systems) have been widely recognised as an inevitable calibration and qualification tool in photovoltaics. Different DASs have been used in many European PV test laboratories since many years. As the cost of the computer and electronic equipment designed for data acquisition steadily decreases, the number of installed DAS for PV application has been also rapidly grown during the last few years. There are at least several good reasons why to install expensive and sophisticated PV Monitoring Systems. The most important are:

- evaluation of proper standards and reference devices based on measurements performed in outdoor conditions (low-cost and reliable irradiation sensors which are mainly Si-sensors, reference solar cells and modules, are sought by both PV manufacturers and research laboratories),
- calibration of PV devices; estimation of the rating performance at Standard Test Conditions[1],
- estimation of Nominal Operating Cell Temperature[2] (NOCT) for PV modules and cells,
- investigation of long term stability and reliability of PV devices and components of PV systems (PV modules and arrays, temperature and irradiation sensors, batteries, charge controllers, inverters, etc.); very often these are services performed according to specific order of PV manufacturers for certification purposes,
- monitoring and acceptance tests of complete PV systems in the field,
- estimation of performance (e.g., investigation of potential cumulated charge and energy gain of PV modules and arrays) of different types of PV devices in strongly changeable conditions which would be difficult or even impossible to settle in laboratory conditions within reasonable costs,
- practical verification of theoretical assumptions and analyses,

[1] Standard Test Conditions (STC) or Standard Reference Conditions (SRC) mean 1000 W/m^2 total irradiance, AM1.5 spectrum and module/cell temperature 25°C.

[2] Nominal Operating Cell Temperature (NOCT) is a fixed temperature that the module/cell would operate if it were exposed to 20°C air temperature, 800 W/m^2 toral irradiance, and a wind speed of 1 m/s.

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- elaboration of possible guidelines for the manufacturers of PV components how to improve their products as a part of developing process.

Obviously the range of tasks proceeded by a given PV DAS is usually limited, e.g., it may be relatively simple system specified only for outdoor calibration of solar radiation sensors or system controlling the energy flow in a big either stand alone or grid-connected PV system in the field. In the following sections only some aspects dealing with measurements of solar irradiation for PV purposes as well as measurement and monitoring of PV modules performance will be described.

Additionally substantial list of references concerning the discussed subjects will be given.

2. Data acquisition systems for outdoor testing of PV modules performance – examples of data presentation

In order to be able to estimate long term performance of the commercial PV modules specialised DAS for outdoor PV modules monitoring was designed in the Solar Lab nearly five years ago and probably it was the first PV DAS designed and installed in Poland[3]. Every ten seconds it measures full I-V characteristic of one of twelve PV modules together with actual insolation and ambient as well as module's temperature. It means that full I-V curve of each module is taken in time interval of about 2 minutes. Such values as short circuit current, I_{SC}, I_{12} (current at 12 V point of the I-V curve that has been assumed as a rating point of charging standard 12 V battery), P_M [module's output power measured at maximum power point (MPP)] and insolation intensity are integrated in time thus allowing to estimate for each module values of cumulated during a day maximum electric charge, charge in the average charging point of a standard 12 V battery, maximum energy gain, and solar insolation energy, respectively. More detailed description of the SolarLab's system may be found in Refs. 1 and 2. In a similar way data measured by two PV DASs designed and assembled in the University of Opole, in March '97

[3] This work was financed by PECO-project PL-932049 linked with MULTI-CHESS 2 (JOU2-CT92-0179).

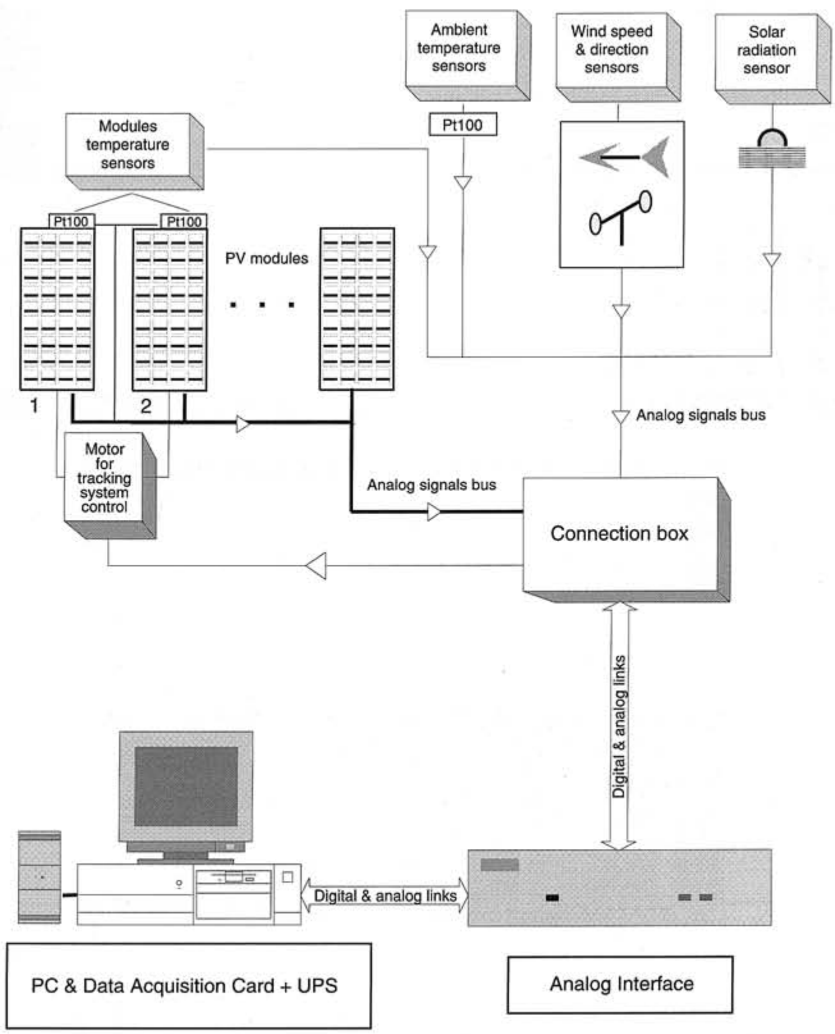

Fig. 1. General scheme of Data Acquisition Systems installed in the Solar Lab of Wrocław University of Technology and in the University of Opole.

and September '98, respectively, are analysed. The older one of the two systems works as a small meteorological station powered by a single module PV system controlled by the same computer as used for data acquisition [3,4]. Every two minutes the PV module is disconnected for about 20 ms from the system for taking its I-V characteristic. Besides the module's performance and battery charging status, the system also monitors meteorological data like solar radiation, wind's speed and direction, atmospheric pressure and humidity. The newer system is a specialised system designed specifically for monitoring up to six PV modules that can be optionally either fixed or single axis sun tracking. At present stage the system stores data measured for two modules only – one is south-oriented, east-west single axis sun-tracking module while the other remains fixed. Compiling data stored by both DASs allows analysing the effect of insolation level, ambient temperature, wind direction and speed as well as sun tracking option on the PV module performance [5]. Global insolation intensity and module's temperature (TC) are measured using ESTI-type double silicon solar cell sensor [6-8] mounted at the modules. Since September '98 global irradiance is also measured at a horizontal plane with Kipp&Zonen CM11 sensor. All systems store data in a continuous way falling into sleep mode during night-time. A general scheme of the systems installed in Wrocław and Opole is shown in Fig. 1. Figure 2 shows presentation examples of measured data on PC monitor's screen for all three systems.

In Fig. 3, cumulated values of the electrical energy calculated at MPP (i.e., time integral calculated at this point), generated by fixed south-oriented modules installed in Solar Lab, have been plotted. To make picture more clear, the results for five chosen modules only, instead of all twelve, are presented. Data were stored in March '95 by DAS during two days characterised by very different insolation. Contrary to sunny day huge spread in amounts of energy cumulated during cloudy day may be noticed though parameters of the all presented modules did not differ as much when measured in laboratory at STC.

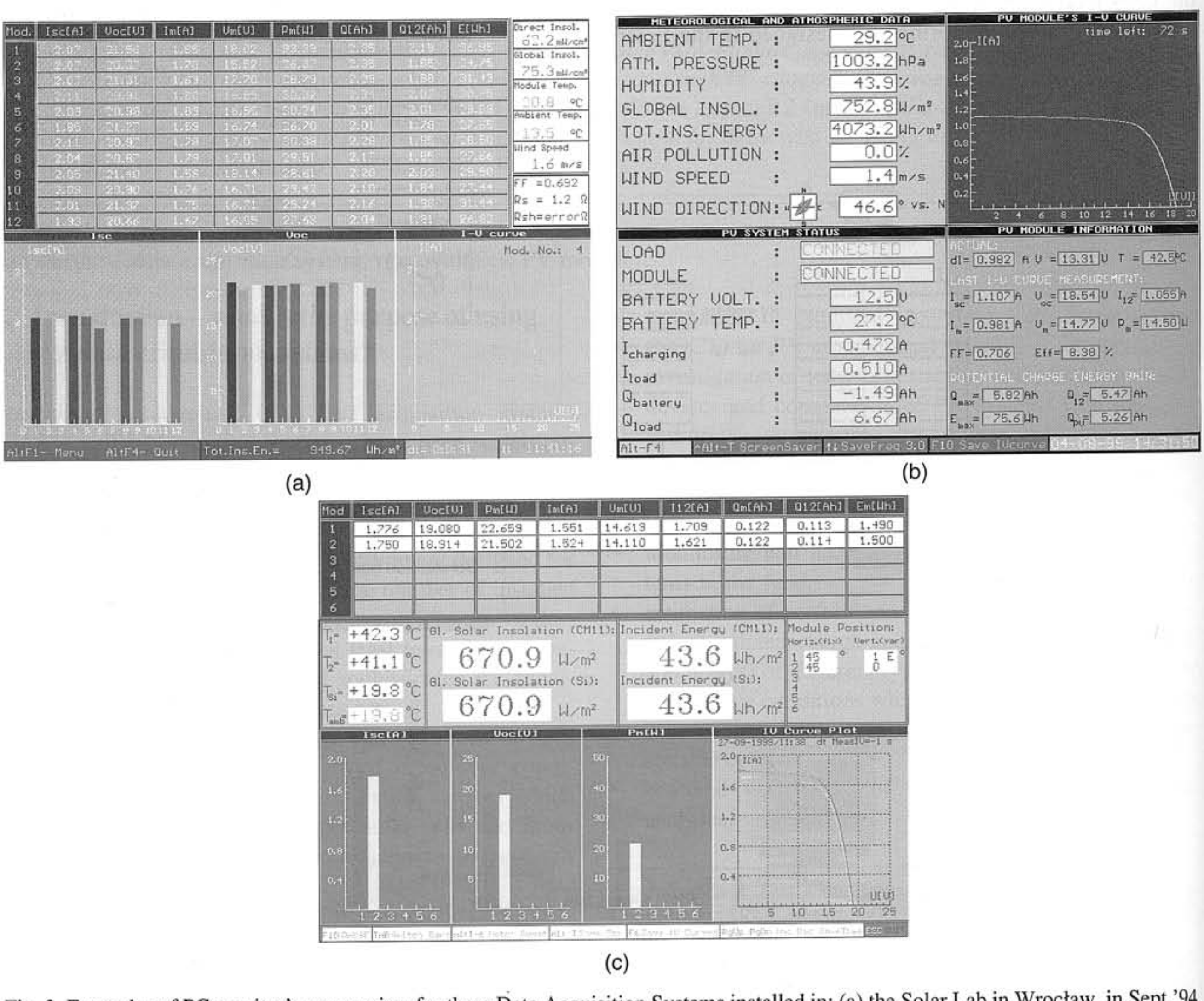

Fig. 2. Examples of PC monitor's screen view for three Data Acquisition Systems installed in: (a) the Solar Lab in Wrocław, in Sept.'94, and the University of Opole, (b) in March '97 and (c) in Sept. '98. All data presented as numbers in tables in (a) and (c) may also be viewed as bar graphs. In (b), in separate windows data corresponding to PV module, PV system status and meteorological unit are presented.

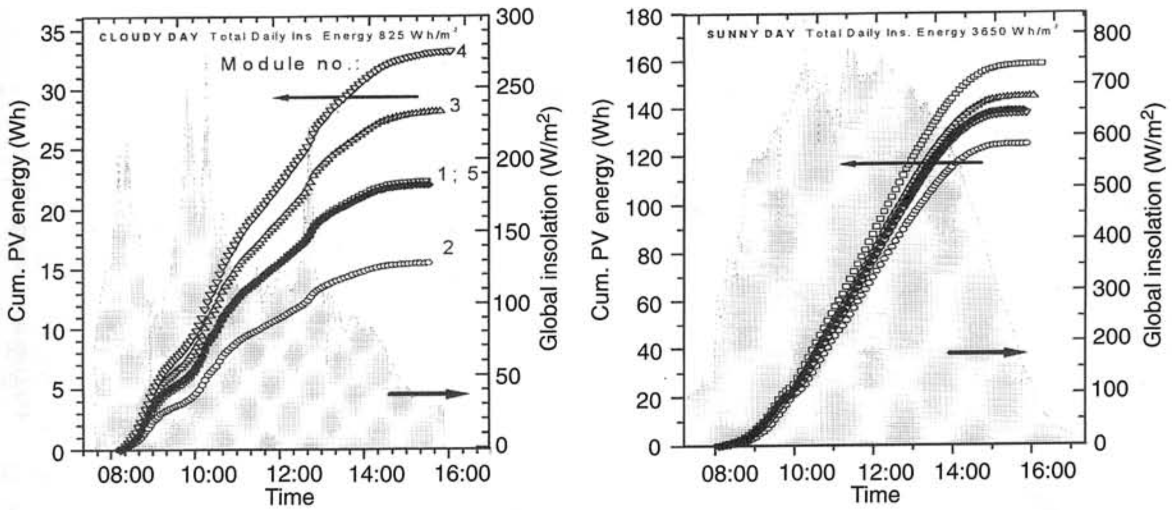

Fig. 3. Plots of cumulated values of the electrical energy calculated at MPP point generated by five fixed south-oriented modules. Data were stored in March '95 by DAS installed in the Solar Lab during two days characterised by very different insolation. Contrary to sunny day huge spread in final amount of energy cumulated by particular modules during the cloudy day may be noticed. Note different scale corresponding to each plot.

Dependence of module's basic parameters like maximum power, efficiency and open-circuit voltage on insolation level is shown for two summer '95 days in Fig. 4. For comparison, all parameters have been plotted in a normalised form. For analysis two modules characterised by different values of I-V curve's fill factor (0.65 and 0.71 at STC, respectively) have been chosen. Again, strong variations in the performance of the two modules is noticeable, depending on the insolation level, though parameters measured at STC for both modules were not as much different.

Data compiled for the period of several months have been presented in Fig. 5 where values of PV energy, cumulated during the day, versus cumulated insolation energy have been plotted for the modules from Fig. 4. It is very clear that lower quality module (lower value of I–V curve fill factor) generates energy not only with lower "rates" but

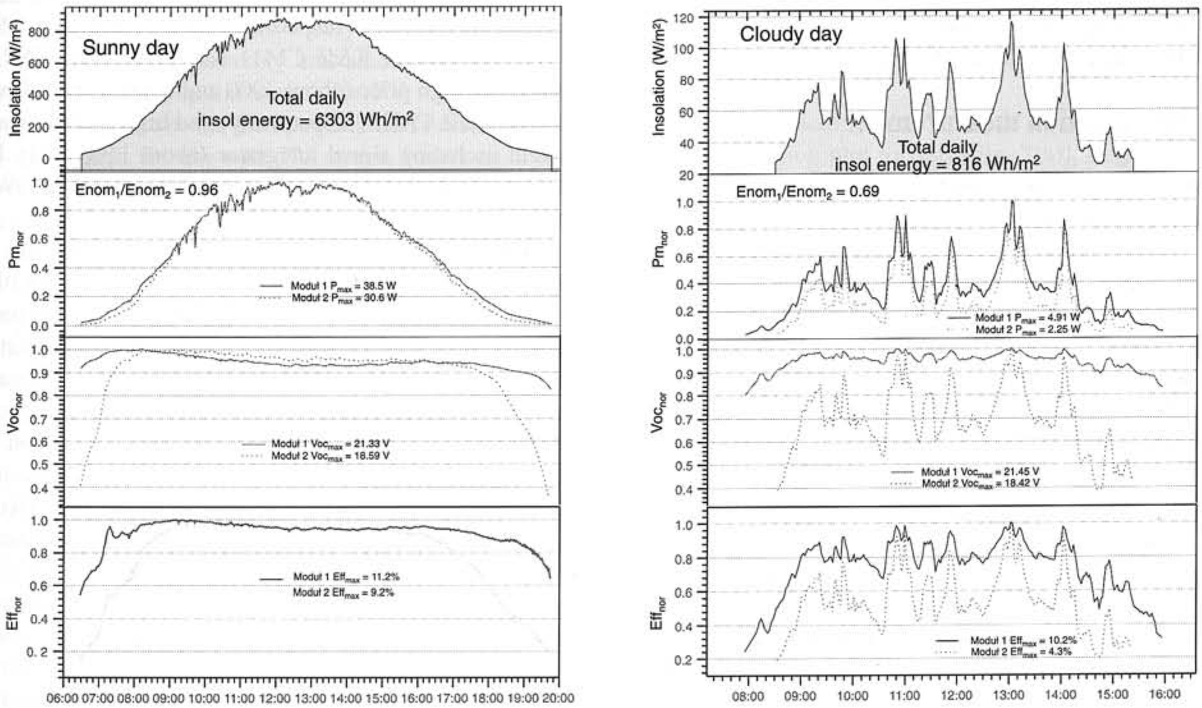

Fig. 4. Plots of normalised values of the maximum power (P_{Mnor}), the open circuit voltage (V_{OCnor}) and the efficiency (Eff_{nor}) measured for two modules characterised by different values of I-V curve's fill factor measured at STC. Data were stored in summer '95 during two days by Solar Lab DAS. Strong variations in the performance of the two modules is noticeable depending on the insolation level though parameters measured at STC for both modules were not as much different. Note different scale corresponding to each plot.

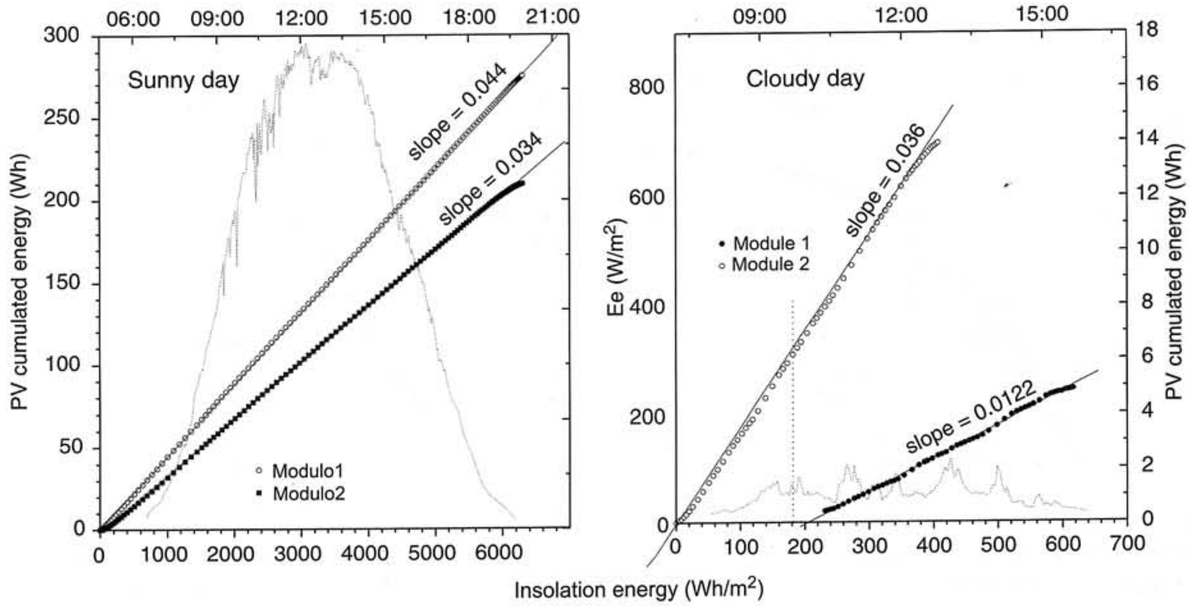

Fig. 5. Plots of values of cumulated energy (time integral calculated at MPP) versus cumulated insolation energy for the modules from Fig. 4. Note that lower quality module (lower value of the I-V curve fill factor) generates energy with lower slope and moreover it "starts" generate much later in the case of cloudy day. Note different scale of energy corresponding to each plot.

moreover, it also "starts" to generate useful electricity much later in the case of a cloudy day.

The presented results are merely the examples chosen to show that relative performance of the PV modules may dramatically change with insolation level leading to possible serious undersizing of the stand-alone PV systems during poor insolation periods in the case when dimensioning procedure has been based on the parameters measured at STC. More detailed presentation and analysis of data acquired by all three DASs may be found elsewhere [1,3,5,8].

3. Solar radiation measurement

Measurement of solar radiation is one of the most important tasks provided by almost every PV monitoring system. Hence, the proper choice of radiation sensor, quality of its calibration and its stability is very important.

To calibrate solar radiation sensor it is necessary to use a proper standard sensor. In general standards for calibration differ to the level instrument, i.e., primary or secondary sensors. The primary standards for solar irradiance are absolute cavity radiometers (e.g., type PMO-6) and they are usually calibrated during prolonged outdoor measurements at high altitudes. Primary reference cell or module is a device which has been calibrated outdoor against primary standard conforming to the current world radiometric reference (WRR). Secondary reference cell or module is a device calibrated in either natural or simulated sunlight against a primary reference cell or an ISO secondary standard reference pyranometer [9,10].

Though outdoor calibration is required for primary standard yet, one should be aware that exactness of calibration may depend on both atmospheric conditions and construction of the sensor [11,12]. In photovoltaic practice basically two types of solar radiation sensors are widely used. The first are thermopile pyranometers which usually have been calibrated as primary reference or the secondary standard sensors. In this group probably the most popular in Europe are Eppley Labs PSP and Kipp&Zonen CM11 thermopile sensors for global radiation measurement. Their main advantages are high accuracy, stability and spectral linearity in whole solar spectrum of practical significance. The disadvantages are long time response (15 and 3 seconds for 95% of final readout for K&Z CM11 and Epply Labs PSP, respectively), high price (about 3000 and 1900 DM for Eppley PSP and K&Z CM11, respectively) and high cost of measuring unit including signal integrator (about 1500 DM). Low level of output signal, usually of the order of few μV/Wm^2, puts high requirements on measuring unit.

For most PV applications properly calibrated the secondary silicon reference cell is sufficient and a lot of effort has been done to establish standard calibration procedures for this kind of sensors [13,14]. A comprehensive review on irradiance monitoring devices and calibration techniques can be found in Refs. 15–17. The importance of low-cost yet highly precise and reliable irradiation sensors for PV utility has been reflected in realisation of three consecutive international intercomparisons (Round Robin Calibrations) on the calibration of photovoltaic reference cells performed during 1984-1995 and involving leading European PV test laboratories [18–22]. The last intercomparison (PEP'93) was initiated by the photovoltaic solar energy project (PEP) of the Technology, Growth and Employment Working Group of the G7 Summit and was carried out from 1993 to 1995 with NREL (National Renewable Energy Laboratory, Golden, CO, USA) as, so-called, Operating Agent. In a project a specific set of reference cells handed in by each participant circulated

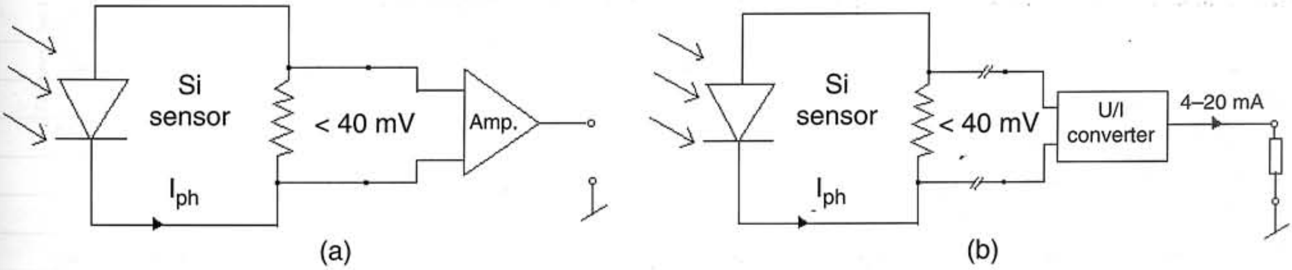

Fig. 6. Basic circuit for measurement solar irradiation using Si sensor: (a) in the case when output signal from the sensor may be directly transmitted on the input of data acquisiting unit and (b) in the case where distance between sensor and data acquisition circuit exceeds ~10 meters and voltage-current converter should be used to avoid possible signal interference.

for calibration. A qualified mean of calibration results established the final world photovoltaic scale (WPVS) [20]. The WPVS sample set consists of 20 encapsulated reference cells belonging to 11 world-wide PV calibration laboratories [21,22].

Research has been carried out on the optimum design and performance of large-area silicon cells, best suited as reference devices [23] and even possible use of silicon cells as an absolute primary irradiation sensors has been investigated under the project named ASPIRE (acronym for Absolute Silicon Primary Irradiance REference) in the frame of JOULE project [24,25]. In '92 the ESTI-Sensor has been introduced to public [6]. It consists of two halves of the same silicon single crystal silicon cell. One half senses irradiance proportional to I_{SC} signal measured as a voltage drop on precision shunt resistor whereas the other half remains open-circuited and serves as temperature sensor [7,26]. The sensor has been widely used in the famous 1000-roof project in Germany and since then it has been probably the most popular sensor for PV solar irradiation monitoring in all over the Europe [27]. ESTI sensor is basically designated for use with PV arrays, based on crystalline silicon modules. However, there is a growing trend to select reference cell tailored to its specific use which means matching sensor's spectral response to that of modules or array to be monitored. Two years ago usability of the ESTI Sensor for the monitoring also silicon amorphous modules has been demonstrated by modifying its spectral curve by adding to its cover broad band filter [28]. This meets expectations of significant part of PV utility for low-cost solar radiation sensor suitable for monitoring PV modules and arrays they are dealing with. When choosing silicon sensor for PV monitoring purposes some requirements for the reference cell as well as measuring circuit should be met. They are as follows:

- cell should be manufactured with highest quality single crystal material guarantying long-term stability of the sensor,
- cell should be characterised by a high leakage resistance to ensure that true value of short-circuited current is measured,
- possibly low sensitivity of the cell to angle of incidence is advantageous when used for global irradiation measurements (cells with textured surface are advisable),
- cell's spectral sensitivity should be at least similar, if not the same, to that of monitored devices, either PV cells and/or modules (see conclusions in Ref. 29),
- cosine response of the sensor and monitored devices should be similar – the ideal case is when the same encapsulation technology was applied (see conclusions in Ref. 30),
- strict resemblance of thermal properties of the sensor package to those of monitored PV modules is not necessary but required if the sensor is also used as reference for module's temperature control as in the case of ESTI type sensor,
- low value of shunt resistor (this should be very stable, e.g., made of manganin wire) should be used to measure cell's short circuit current; voltage drop on the resistor should not exceed 40–50 mV under irradiation 1000 W/m^2,
- calibration factor of cell's should be calculated by forcing calibration plot to zero [Fig. 7(a)], [14],
- high-quality measuring circuit (possibly high value of CMMR and low values of thermal drifts and polarisation currents of the signal amplifying circuit). In the case of long distance between sensor and acquisiting unit voltage-current converter may be needed for reliable data transfer (see Fig. 6),
- cell's recalibration, at least, once per year is recommended.

More technical details dealing with calibration procedure and requirements for encapsulant material of the reference cell according to IEC standard may be found in Ref. 9.

Several ESTI-type sensors have been manufactured and calibrated in Solar Lab [7]. They were successfully applied in monitoring systems installed in Wrocław and Opole. Example of set of calibration plots necessary for irradiation and cell's temperature monitoring for one of the sensors is shown in Fig. 7. To simplify calibration process of the cell's half used for temperature monitoring measurements were performed only in-lab using setup designed and constructed in Solar Lab [1].

Appendix. Basic IEC and ISO tests and standards for photovoltaic application.

Normative ref.	Description	Code
Module qualification testing		
IEC 1215–10.1	Visual inspection	VI
IEC 1215–10.2	Performance at STC	PS
IEC 1215–10.3	Insulation test	IN
IEC 1215–10.4	Measurement of temperature coefficient	TCO
IEC 1215–10.5	Measurement of nominal operating cell temperature	NCT
IEC 1215–10.6	Performance at NOCT	PN
IEC 1215–10.7	Performance at low irradiance	PL
IEC 1215–10.8	Outdoor exposure test	OE
IEC 1215–10.9	Hot-spot endurance test	HSP
IEC 1215–10.10	UV exposure test	UVE
IEC 1215–10.11	Thermal cycling test (50 and 200 cycles)	TC50&TC200
IEC 1215–10.12	Humidity freeze test	HUF
IEC 1215–10.13	Damp heat test	DAH
IEC 1215–10.14	Robustness of terminations test	ROB
IEC 1215–10.15	Twist tests	TW
IEC 1215–10.16	Mechanical load tests	MEL
IEC 1215–10.17	Hail impact tests	HAR
IEC 891	Procedures for temperature and irradiance correction to measured I–V characteristics of crystalline silicon PV devices	PS/TCO
IEC 904–1	Measurement of PV current-voltage characteristics	PS
IEC 904–2	Requirements for reference solar cells	
IEC 904–3	Measurement principles for terrestrial PV solar devices with reference spectral irradiance data	SR
IEC 904–7	Computation of spectral mismatch error introduced in the testing of a PV device	SR
IEC 904–8	Guidance for the measurement of spectral response of a photovoltaic (PV)	SR
IEC 1829	Crystalline silicon photovoltaic (PV) array – On-site measurement of I–V characteristics	OAT
IEC 9846	Solar energy – calibration of pyranometer using a pyrheliometer	PYP
IEC 9059	Solar energy – calibration of field pyrheliometers by comparison to a reference pyrheliometer	PYP
IEC 9847	Solar energy – calibration of field pyranometers by comparison to a reference pyranometer	PYS

4. Measurement of I-V characteristics and analysis of performance of PV modules and/or PV arrays

In the case of single solar cells light I–V characteristics may be relatively easily carried out by using controlled power supply with the high current output of operational amplifier type [31]. Such equipment enables measurement of I–V curve expanded into three quadrants. Unfortunately it is not technique applicable in practice for measurement of larger PV arrays. Here the best method is use of dynamic load, either transistor (usually MOS) or capacitor.

On-site measurements and regular analysis of complete current-voltage characteristic of PV array is of immense diagnostic value. This is usually the best method for identifying faulty cells and/or modules, mismatch losses, shadowing as well as ageing and degradation effects. By comparing scans on subgroups of an array with those of a whole array mismatch effects may be studied. Even the subtle impact of dust deposition on plant performance can be assessed by repeated scans before and after cleaning of selected arrays [32,33].

The basic rules for assessment of I–V curves of photovoltaic devices are formulated in IEC–891 and IEC–904 standards [34–36]. Procedures recommended for data acquisition, analysis and on-site measurements are given in Ref. 37. These documents describe procedures that can be recommended to use for measurement, analysis and presen-

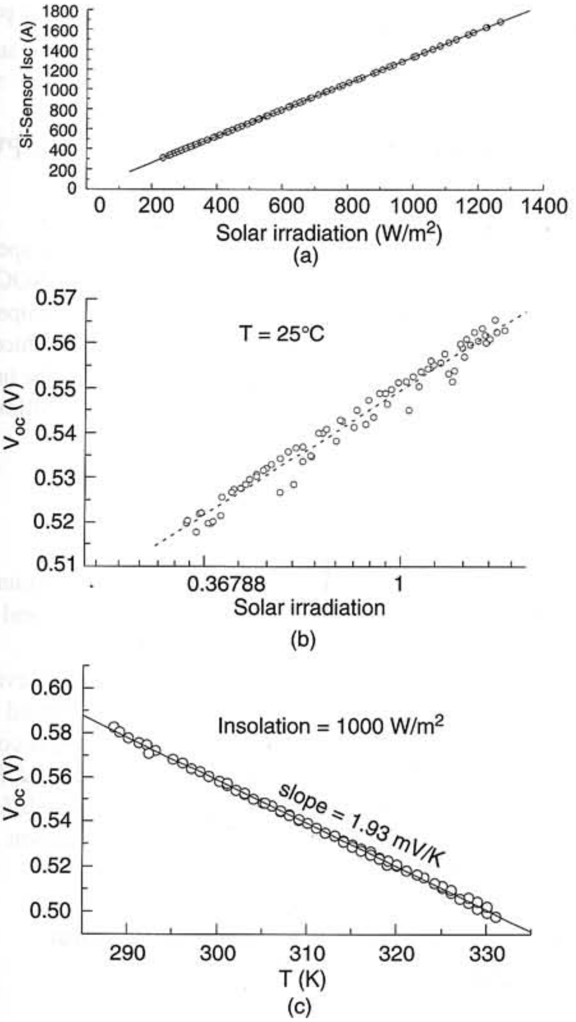

Fig. 7. Set of charactersitics measured in the Solar Lab for double (ESTI-type) cell Si-sensor. Calibration constants calculated using these curves can be stored in the memory of the electronic unit of the sensor to enable simultaneous measurement of solar irradiation and sensor's temperature. Only calibration against K&Z CM11 used as primary sensor (a) was performed outdoor while two other characteristcs were measured indoor using laboratory setup. Some spread of data that can be seen in (b) results from small difference (~1–2°C) in actual temperature of the surface of measuring brass table against readings from Pt100 sensor inserted inside the table during heating and cooling cycles. Note that calibration factor that is to be determined by from (a) should be calculated by forcing plot to zero point.

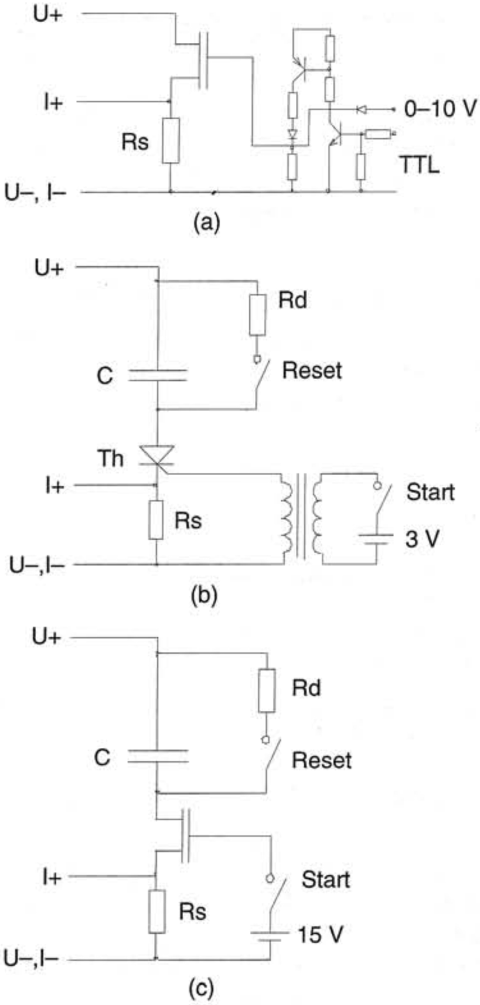

Fig. 8. Basic circuits that can be used for taking I–V curve of PV modules and arrays, (a) with MOS transistor as voltage-controlled load, (b) with capacitor as a load and thyristor as a switch [34] and (c) with capacitor as a load and MOS transitor as a switch. Circuit shown in (a) has been used in Solar Lab DAS. It allows for additional using of TTL signal for short-circuiting of tested PV module and continous sampling the ISC meanwhile enabling using the same PC-programmable sweeper-type signal to measure full I–V curve of another PV module.

tation of monitoring results from PV plants. The methods presented in there have been developed specifically for the PV Demonstration Programme managed by the Commission of the European Communities Directorate General for Energy (DG XVII) and were used also for the monitoring of projects under its THERMIE programme, taking into account recommendations of the above mentioned IEC/TC82/WG3. Basic circuits that can be used for taking I–V curve of PV modules and arrays by means of a dynamic load are shown in Fig. 8. The circuit shown in Fig. 8(a) has been used in Solar Lab DAS [1,31]. It allows taking I–V curve of the single modules and PV arrays with peak power up to few kWp. By setting TTL signal into high state tested PV module becomes short-circuited for continuous sampling of I_{SC}. Using this method only single sweeper-type voltage supply is required for consecutive measurements of many PV modules. It can be used for dynamic modulation of channel's resistance of MOS transistor and taking I–V curve when the signal TTL is set low. The circuits from Figs. 8(b) and 8(c) using capacitive dynamic load were developed specifically to measure big PV plants with peak power exceeding even 100 kWp [32,33,37]. The product of Rd and C is time constant for capacitor discharge. To avoid the errors resulting from time dependent processes in PV array values of Rd and C should be chosen sufficiently high to leave enough time for I–V curve sampling. According to Blaesser's suggestions it should not be lower than about 10 ms [37].

4.1. Extrapolation of outdoor measurements of I–V characteristics to standard test conditions

To eliminate the influence of the instantaneous values of irradiance and temperature, and to be able to compare measurements performed on the same array under different ambient conditions, I–V characteristics have to be extrapolated to the same STC.

There exist several procedures proposed for correction of I–V of PV solar cell (module) to STC. They give different extrapolation errors depending mainly on level of actual irradiance for which I–V curve was taken [39]. Currently two procedures are usually recommended for translation of I–V curve of PV solar cell (module) to STC.

IEC–891 standard [35]

$$I_2 = I_1 + I_{sc}\left(\frac{I_{SR}}{I_{MR}} - 1\right) + \alpha(T_2 - T_1) \tag{1}$$
$$V_2 = V_1 - R_s(I_2 - I_1) - K\,I_2(T_2 - T_1) + \beta(T_2 - T_1)$$

Blaesser's method [33,38]

$$I_2 = I_1 \frac{E_2}{E_1}[1 + \alpha(T_2 - T_1)] \tag{2}$$
$$V_2 = V_1 + \beta(T_2 - T_1) + \frac{kT}{q}\ln\left(\frac{E_2}{E_1}\right) - R_s(I_2 - I_1)$$

where α and β are the experimentally determined thermal coefficients of current and voltage, respectively and K is, so called, curve correction factor (e.g., $K = 1.25\times10^{-3}\Omega/°C$ typically for crystalline silicon cells). Index 1 indicates the measured data, index 2 labels the new temperature T and the irradiation and conversion results for I and V. I_{MR} and I_{SR} are the values of short-circuit current measured at the standard irradiance and in global in-plane irradiance, respectively. Coors *et al.* [39] have shown that method used by Blaesser leads to even smaller errors while not requiring the ambiguous K factor value. However, one should be aware that curve transformation error increases when there exists serious spectral mismatch between tested device and irradiation sensor.

Another method of extrapolation of I–V characteristic to STC is fitting of measured curve to the parameters of either single or double diode model. However, this method requires extensive computation and though giving excellent results it is rather of minor practical significance [39]. Usually the parameters of PV device stated by manufacturer on the nameplate are the values that were measured under Standard Test Conditions or close to those. Performance of the PV module does not usually depend, in a straightforward way, on insolation conditions [3–5]. For high latitude locations like middle and northern Europe random nature of the weather and climate conditions and mainly incident solar energy reaching the earth surface makes performance rating procedures even more difficult and complex. This problem is widely discussed by Bücher in Refs. 40–42 who introduces concept of, so-called, "true module rating" for more realistic performance rating of PV modules. Practical examples of PV modules calibration and qualification procedures are given in Refs. 43 and 44.

4.2. Determination of working temperature of the PV module

Many manufacturers of PV modules specify nominal operating cell temperature for their products. Rating at NOCT benefits modules and systems that operate at lower temperatures and reduces the differences between power produced under field conditions and STC. Knowing NOCT value one may estimate module's working temperature using following formula [44]

$$T_c(°C) = T_a(°C) + \left(\frac{NOCT(°C) - 20°C}{800\ Wm^{-2}}\right)G(Wm^{-2})$$

where T_a is the ambient temperature, NOCT is the nominal operating cell temperature, as given by manufacturer and G is the global in-plane irradiance ($G > 600\ W/m^2$).

Comparison of photovoltaic module performance evaluation methodologies for energy ratings may be found in Ref. 45. Quite recently Blaesser has introduced simple concept of reduced I–V characteristics that can helpful for intercomparison of the I–V curves measured under different ambient conditions [46]. Examples of application of this concept may be seen in Ref. 5.

5. Concept of modular PV data acquisition systems

Usually every PV monitoring system is designed to meet specified requirements and very often it is "closed" for further extension after final installation. This is particularly the case when for data acquisition specialised PC card was used where number of measuring channels and binary input/output is limited. Complexity of installation, usually high cost of the commercially available general purpose data acquisition systems equipment as well as "tying up" PC computer to the system are another disadvantages of such solution. To overcome these limitations we developed specialised fully self-contained modules that we called PVDA-Modules. These modules may be applied in either photovoltaic test laboratories or by PV systems installers and users. Each PVDA-Module is ready for application for which it is specified. It is based on 8-bit PIC (RISC type) family microcontroller and communicates with PC in both directions via RS485 bus. Contrary to RS232 this bus allows controlling of DAS from distance as long as 1.2 km at 100 kB baud rate. Since each PVDA-Module has its own unique address so there is no practical limit for the type and number of the used modules (up to 256 DAS Modules may be used in one DAS). Module starts transmission of the gathered data after properly addressed request received from PC, otherwise command is ignored. The scheme of the modified modular version of the PV monitoring system with PVDA-Modules is shown in Fig. 9.

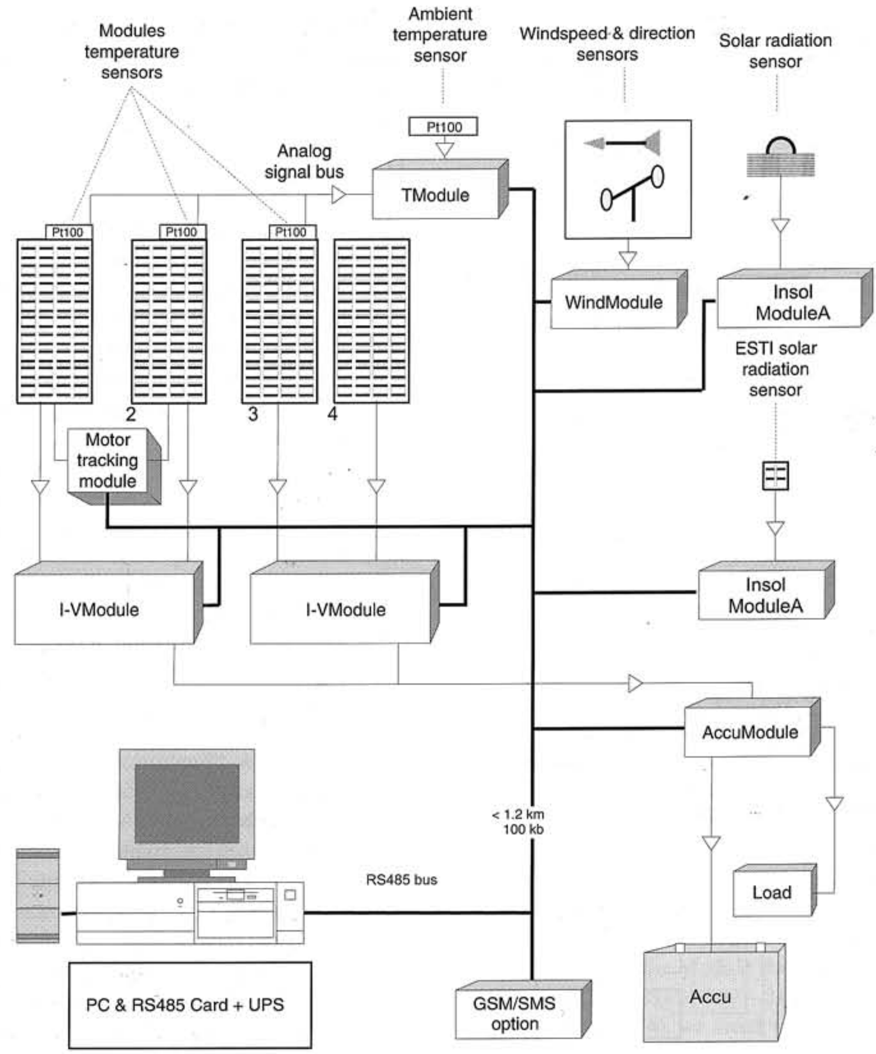

Fig. 9. The general scheme of modular data acquisition system. Easily subjected to electromagnetic interferences analogue signal lines are replaced by digital RS-485 bus. Each measurement is carried out and suitable data are stored "in field". PC communicates with a chosen module using one of 0.255 unique addresses. The whole system may be easily extended by additional components to be monitored without interrupting actual measurement and data acquisiting flow.

Following PVDAS-Modules have been developed in SolarLab so far (Fig. 10):

- IVModule-A – ready-to-use module for measurement of I–V curve of the PV modules and arrays up to 1 kWp (with MOS power transistor as active load). Built-in integrator allows to calculate potential cumulated charge and energy in at Isc, Im, and Pm points, respectively. If suitable command has been received I–V curve may be stored in external EEPROM for later transmission to PC. Measurement is performed with ultra-low power 12-bit series A/D converter and automatically adjusted range using programmable high performance amplifier for both current and voltage sampling. IVModule may be initialised either manually or from PC. Default sampling conditions like frequency of measurement, number of samples, integration interval (for cumulated charge and energy calculation) may by changed from PC and stored in EEPROM as default values. If either of InsolModules and/or TModule is present in the system as well, then PC examines them for actual values of insolation and temperature,
- InsolModule-A – module for insolation measurement with use of commercial pyranometer, e.g., K&Z CM11,
- InsolModule-B – module for measurement insolation and temperature using ESTI sensor or any other silicon sensor. Both types of InsolModules have built-in integrator for cumulated incident solar energy calculation. Calibration constants must be written into module's memory using PC. This type of PVDA-Module is similar to ESTI-Log developed in JRC [47],
- TModule – module for temperature measurement. Presently only module for use with Pt100 thermoresistors (4 channels) has been developed.

The following PVDA-Modules are to be developed in Solar Lab in the nearest future:

- IVModule-B – module functionally similar to IVModule-A but with capacitive load enabling to measure PV arrays exceeding 10 kWp,

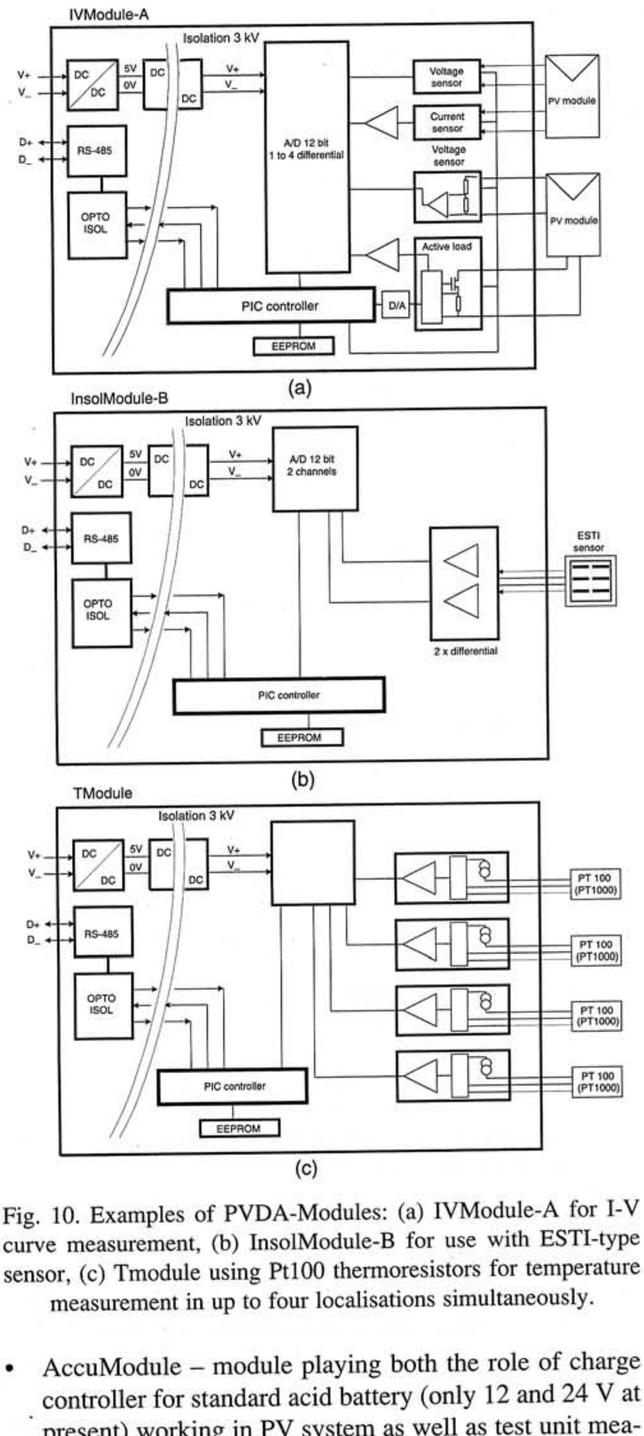

Fig. 10. Examples of PVDA-Modules: (a) IVModule-A for I-V curve measurement, (b) InsolModule-B for use with ESTI-type sensor, (c) Tmodule using Pt100 thermoresistors for temperature measurement in up to four localisations simultaneously.

- AccuModule – module playing both the role of charge controller for standard acid battery (only 12 and 24 V at present) working in PV system as well as test unit measuring charge/discharge currents with integrator calculating real charge coming to or out the battery; typical threshold voltages are stored in module's EEPROM but they may be changed from PC and then corrected according to real battery temperature

Besides of low cost the another advantages of the PVDA-Modules is extreme simplicity of their installation and almost unlimited extendibility. DAS system consisting of the appropriate PVDA-Modules after initiallisation may work without any communication with PC. All data (mainly integrals) are periodically stored in the EEPROM of the microcontrollers and will not be lost even if the power has been cut off.

Software for the overall control of the DAS may be written in any programming language under either MSDOS® or MSWindows® control or with use of specialised software like HPVEE®, LabView® or TestPoint®.

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