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Improved Outdoor Monitoring of Photovoltaic Modules

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Abstract: The Centre for Renewable Energy Systems Technology (CREST) has been operating an outdoor measurement facility for testing photovoltaic (PV) modules since 1998. The facility is used to continuously measure the performance of a range of commercial and prototype modules, by scanning full I-V characteristics every ten minutes with synchronous measurements of ambient and module temperatures and broadband and spectral irradiance. The trend for increasingly high power PV modules and increased demand for channels has precipitated the next stage of development for the CREST system. A number of lessons have been learned from the past system which are indicated in this paper with a thorough system analysis, along with a description of the standard measurement cycle currently in operation. Then follows a full technical description of the new system, including the hardware design and software development.

1. Introduction

For a number of years, the focus of research conducted by the PV systems group at CREST has been on realistic outdoor performance analysis and modelling at the module level. In contrast to the controlled environment of a laboratory, study of the outdoor performance of PV modules requires a much larger quantity of data, since analysis will rely far more on statistical methods to overcome the natural variability of the test conditions. Accurate measurements of DC power (module current-voltage characteristics), module temperatures and meteorological data are critical, with the additional challenge of operating continuously in all weather conditions.

This paper presents a description of the evolution of the CREST Outdoor Measurement System. Development of such a system is continuous as the specification demands for data tend to change to reflect the current thrust of research. Also, improvements can always be made in the basic data requirements as better measurement equipment becomes available or affordable. Perhaps most importantly however, is that the measurement system itself is experimental since there is no prescribed outdoor system specification for PV research. Results of experience from one implementation, good or bad, necessarily have an impact on the design of the next.

The CREST Outdoor Measurement System (COMS) is currently in its second incarnation, referred to as COMS-2 in the following, commissioned in September 2002. This version of the system is described in the following section and some of the strengths and weaknesses discussed. The upgrade to COMS-3 is now ready to go live, significantly extending the measurement possibilities at CREST. A description of this new version is followed by an error analysis, comparing the two systems implementation.

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2. The CREST Outdoor Measurement System Mk2

**Description of the system**

The CREST rooftop-mounted PV module monitoring system was originally commissioned in May 1998. In September 2002 the system was upgraded substantially, with the PV module test capacity increased from 20 to 50 channels, recalibration for all instruments and development of improved control/logging software. A schematic of the complete system is shown in Figure 1.

![Schematic of the COMS-2 arrangement](image)

**Figure 1:** Schematic of the COMS-2 arrangement

Measurements of module current-voltage (I-V) curves are carried out using a Keithley Instruments 2400 series source-measure unit. In effect, this is an accurately controlled 4-quadrant power supply with current and voltage measurement capability. Back-of-module temperatures are monitored with thermally bonded PT100 sensors, measured by the Keithley unit with a four-wire connection. To measure multiple PV modules, the Keithley unit inputs are switched sequentially through an 8-pole, 50-channel multiplexer designed and built in-house (Figure 2a, behind the modules in Figure 2b). The channel selection is controlled via digital outputs on the Keithley unit, interpreted by a small micro controller in the switchgear housing. The Keithley unit itself is controlled directly by the measurement PC over a GPIB bus.

Global and plane-of-array irradiance are measured with Kipp & Zonen thermopile pyranometers (foreground, Figure 2b). The small voltage outputs from these instruments are amplified on the roof before the cable runs to an analogue-to-digital conversion (ADC) board in the PC. The housing for the amplifier also contains a current source for the resistive sensor measuring ambient air temperature. The voltage drop is measured on the same ADC board to infer resistance.

Spectral irradiance is measured with a scanning monochromator type spectroradiometer (Instruments S.A. 270M). A silicon detector measures from 300-1040nm and an indium-gallium-arsenide (InGaAs) detector extends the range to 1700nm. Measurements are taken in 10nm steps, requiring 141 individual samples per scan. The monochromator itself resides inside the building and is so protected from large temperature variations. The input on the roof is an integrating sphere (bottom-right, Figure 2b), connected to the
monochromator by a fibre optic cable. The spectroradiometer is connected to the PC through a serial port.

![Figure 2: a) Multiplexer, b) Rooftop elements of COMS-2](image)

Data collection is managed by in-house software (implemented in Delphi) running on the PC. Meteorological data are sampled and logged every 10 seconds, spectral irradiance, I-V curves and module temperatures are measured every 10 minutes, with measurements of each module I-V curve temporally bracketed by additional thermopile readings, to assess stability of the conditions. The spectroradiometer runs on its own software resident on the same PC, hence the spectral irradiance data are intercepted by the central system control application before all of the data is compressed and added to storage.

**Weaknesses of the system**

Combining the shutter open/close, detector switchover and scan speed of the monochromator, a complete spectral irradiance measurement requires approximately 2 minutes. This leads to a significant proportion of spectral measurements being corrupted by changing levels of broadband irradiance during acquisition. Such changes are not recognised by the monochromator, which will continue to measure regardless, resulting in a measurement file that, to the system, appears to be sound. In addition, since the PV modules are tested sequentially, the electrical measurements are not necessarily simultaneous with the spectrum measurement. Some channels are still being measured even after the spectroradiometer scan has been completed, necessitating further checks on the stability of conditions between the two events. To overcome such issues, COMS-2 uses the set of 10-second pyranometer measurements of broadband irradiance that correspond to the 2-minute scan time of each complete spectrum measurement to assess the stability of the conditions during the acquisition of all data. By comparing sequential pyranometer measurements, it is possible to determine not only whether the irradiance was stable over the whole spectrum scan, but also for any trailing I-V measurements. Although this approach has proved successful in improving data quality, a significant number of data are rejected for analysis due to the short timescale variability of UK weather. It was hoped that a significant reduction in measurement time would be accomplished during the COMS upgrade to version 3 to increase usability of the measured spectral data.

The Keithley unit is compact, rugged and has proved very reliable (running almost continuously for six years). However, limitations exist regarding its use for measuring I-V curves. The most important is that the unit can sink a maximum of 60 Watts, limiting the
rating of modules that can be tested to a figure rather small by the standards of the newest PV products available. Furthermore, this power limit is compounded by additional voltage mode limits of 60 Volts at 1 Amp or 20V at 3A, with implications for modules of different materials or cell string configurations. There are yet further restrictions for four-wire measurements. Hence, another specification in the COMS upgrade was the lifting of these limits, necessitating a larger capacity power source/sink.

Finally, a new arrangement was specified for measurements of meteorological data, to both improve the logging accuracy of the sensors implemented in COMS-2 and to increase the number of channels. The new system would then include several different types of irradiance sensor and start continuous logging of parameters of interest in other renewable energy technologies.

3. Description of the CREST Outdoor Measurement System Mk3

Improvements to existing hardware

The upgrade to COMS version 3 has surpassed the original specification. In the first phase of development, the usage efficiency of the existing hardware has been dramatically improved by a complete re-write of the control software, in a move to the LabView software suite developed by National Instruments. Control of the spectroradiometer, which was previously handled by the manufacturer's application software, is now embedded in the main control application. By taking control of the various stages in the spectrum measurement scan, the process has been optimised to complete in just over one minute (reduced from almost two minutes), greatly reducing exposure to irradiance instability.

Control of the Keithley unit has also been much improved. The LabView interface is more intuitive than the text-based Delphi language for programming instrumentation control. This has resulted in significantly improved setup procedures for the Keithley unit, resulting in a reduction in the time for both I-V sweeps and switch control. The complete all-channel I-V and temperature measurement cycle time has been reduced by a factor of three (taking now 4.5 seconds to measure the temperature and I-V curve of each module). The Keithley unit and existing multiplexer remain in service as the 'Low-Power PV Measurement' sub-system.

System Hardware additions

The addition of an all new ‘High-Power PV Measurement’ sub-system has increased the total number of channels by 64 through the use of a commercial high-density switch chassis (National Instruments PXI), with expansion capacity for a further 64 channels. The switch chassis contains three different types of multiplexer cards to perform:

- 4-pole, 64-to-1 routing for back-of-module PT100 measurements (four-wire connection).
- 2-pole, 64-to-1 routing for high-voltage sense, high-impedance path for I-V curve measurements (first pair of a four-wire connection).
- 1-pole, 64-to-1 relay driving to switch external, 2-pole high-power relays (the current path to complete the I-V curve four-wire measurements).

The PT100 resistance measurements are made with a National Instruments (NI) M-series data acquisition (DAQ) card and signal conditioning terminal block (SCC). This block contains a stabilised current source and high-impedance voltage sense, connected directly to the common output of the 4-pole multiplexer.

I-V measurements are made with a four-quadrant power supply (Kepco BOP series). This unit allows four-wire I-V measurements for module (or indeed small system) powers up to
1kW, with voltage and current limits of 100V and 10A. The Kepco unit voltage sweep is controlled by an external reference from a NI DAQ card analogue output. Current monitoring is output by the Kepco as a proportional voltage (-10 to 10V) and is read directly on the NI DAQ card, while the voltage sense is first attenuated by a 10:1 module in the signal conditioning block. The power (current-carrying) terminals of the Kepco are multiplexed to the PV modules under test via a custom-built switchgear unit of high-power relays. 10A multiplexer cards for the PXI chassis are not available in high enough density because of the physical size of the components, but the chassis still maintains control through the relay driver card mentioned above. 2-pole, double-throw relays have been used in the power multiplexer to enable connection of arbitrary loads (e.g.: short- or open-circuit, fixed load, maximum power point tracker) independently to each channel between the I-V measurements (which are still made at ten minute intervals). A schematic of the high-power system is shown in Figure 3:

![Figure 3: COMS-3 High-Power PV Measurement Sub-system](image)

Improvements have also been made to the acquisition of meteorological data with the addition of a commercial logger (Campbell Scientific CR10) and a number of new sensors. These include a Kipp & Zonen CM22 thermopile pyranometer (the new primary measure of irradiance for the I-V curve measurements), several silicon-based pyranometers at different inclinations, calibrated reference cells of the major PV technologies, a diffuse irradiance sensor and collection streams of different weather data for environmental monitoring and modelling pertinent to research work at CREST (relative humidity, wind speed and direction).
The synchronisation of the disparate system elements is at the core of the control software. Hardware and software checks do not allow the possibility of measurement corruption through incomplete switching of the various multiplexers with high consideration also given to the control and triggering of I-V data measurement. With this strict control over the timing, temperature and I-V curve measurement for each module in the high-power sub-system takes only 2 seconds, including switching. Stability data collection has been dramatically improved with the system now providing quarter-second measurements of irradiance from up to three sensors when any one of the Spectral Irradiance Measurement, Low-Power PV Measurement or High-Power PV Measurement sub-systems is active.

4. Error Analysis Comparison for the System Upgrade

Broadband Irradiance Measurement
The CM11 model pyranometer used in COMS-2 has a 95%-response time of 12s, and errors due to linearity (±0.6%), thermal effects (±1%) and acceptance angle effects (<±3% at 80° incidence), giving an overall declared accuracy for hourly irradiance measurements of 3%. The cable losses associated with the COMS-2 meteorological data measurements are treated as negligible, since the total cable resistance is calculated at less than 1 Ohm and the input impedance of the ADC card is in the range of MΩ. The 0-5V signal range and 12-bit card give a digitisation error that is also negligible. Since the measurements are digitised on the roof in COMS-3, the new system also has zero losses in the run to the PC. The largest source of error in the COMS-2 system was associated with the rooftop amplifier circuit. The amplifier input has a maximum offset error of ±250μV (±50Wm⁻²) at 25°C with an additional temperature dependence of ±3μV/°C (±0.6Wm⁻²/°C). The gain is accurate to ±0.5% (±5Wm⁻² at 1000Wm⁻²) at 25°C with an additional ±100ppm/°C (±0.1Wm⁻²/°C at 1000Wm⁻²). The greatest concern was the offset on the amplifier input, which is subsequently magnified. Since it is not known how this varies over time, all pyranometer data from the COMS-2 system underwent an offset correction based on the average zero offset of the night time measurements of the 24-hour period in question. This effectively levels the input offset error at the average night time temperature for each day’s measurements. This leaves a temperature-dependent offset error of the order 6Wm⁻² (based on a daytime-night time air temperature difference of typically 10°C). Combining this with the CM11 and amplifier gain errors yields an overall maximum error less than ±5% for measurements exceeding 500Wm⁻², rising to ±10% at 100Wm⁻² for COMS-2. The CM22 model pyranometer used in COMS-3 has a 95%-response time of 5s, and errors due to linearity (±0.2%), thermal effects (±0.5%) and acceptance angle effects (<±3% at 80° incidence), giving an overall declared accuracy for hourly irradiance measurements of 2%. The sensitivity of the CR10 datalogger is sufficient to measure the weak thermopile voltage signals directly, so there is no error source associated with amplification. The inputs of the CR10 used for the thermopile measurement have a maximum error of ±50μV (±5Wm⁻²) and a digitisation resolution of 3.33μV (±0.4Wm⁻²). Combining the CM22 and CR10 errors yields an overall maximum error less than ±3% for measurements exceeding 500Wm⁻², rising to ±7% at 100Wm⁻² for COMS-3. In practice, initial testing puts the actual error considerably lower than this worst-case scenario.

Spectral Irradiance Measurement
The only elements of the spectroradiometer system on the rooftop are the integrating sphere and covering dome. The integrating sphere is specifically designed to accept
radiation over $2\pi$ steradian and features an almost ideal cosine response. Since the system is calibrated in situ, optical losses in the cable and monochromator are accounted for. The calibration errors are wavelength-dependent, but are limited to less than 5%.

The dominant error in the measurement of the complete spectrum arises from changing sky conditions over the scan time. In the COMS-2 implementation, stability was checked using ten-second thermopile data. This was not ideal, since even ten seconds can be a long time compared to cloud movement on a windy day and such a frequency is in the order of the sensor response time. Matters are very much improved in COMS-3: not only has the spectrum scan time been almost halved, the stability measurements are now made every 250 milliseconds with both a thermopile and a fast-response silicon detector. While it is difficult to summarise the improvements numerically, it is clear that the impact on data quality and availability will be profound.

**PV Measurements**

In COMS-2 and now the Low-Power PV Measurement sub-system in COMS-3, the I-V measurements of each module are taken by programming the Keithley unit to sweep through set points in voltage source mode, from slightly reverse bias to slightly exceeding $V_{OC}$. The stated maximum error as a voltage supply is ±(0.02% + 2.4mV). Similarly, the Keithley unit measures the current response of the module during the voltage sweep with a maximum error of ±(0.07% + 570μA).

For the high-power sub-system in COMS-3, the only measurement taken directly from the Kepco unit is the current sense, with an output accuracy of ±0.1%. This is combined with the NI DAQ analogue input accuracy of ±3mV to give an overall maximum error of ±0.3% for current measurements down to 1A. The error in the voltage measurement is a combination of the same NI DAQ analogue input accuracy and ±(0.14% + 6.5mV) from the voltage attenuator to give an overall maximum error of ±0.2% for voltage measurements down to 10V.

The maximum error associated with the back-of-module temperature measurement PT100 is ±0.8°C at 100°C. When the Keithley unit is employed to make the resistance measurement, it does so with a maximum error of ±(0.08% + 0.03Ω) resulting in an overall module temperature measurement accuracy of ±1°C over the range −10°C to +100°C.

Using the NI signal conditioning module, yields an overall module temperature measurement accuracy of ±2°C over the same range.
5. Conclusions

Considerable improvement in the capabilities of the CREST Outdoor Measurement System has been presented. The most significant may be summarised as the addition of a new high-power I-V curve measurement sub-system, allowing four-wire measurements of modules or mini-systems up to 1kW, with the facility to independently and arbitrarily load each test channel between I-V curve sweeps.

Great reduction in measurement times for the pre-existing hardware has been achieved through a new choice of software control, increasing data availability previously reduced by temporal instability of lighting conditions.

New sensors and logging equipment has increased accuracy of critical meteorological parameters and extended the usefulness of the system outputs.

At this time, the first elements of the new system are undergoing outdoor testing. The completed facility and collected data will be offered as a research tool serving the UK and wider PV research communities.

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7. Resources

Keithley Instruments: http://www.keithley.com/
Kepco: http://www.kepcopower.com/
Kipp & Zonen: http://www.kippzonen.com/
Finder Relays: http://www.findernet.com
Campbell Scientific: http://www.campbellsci.com/
Delta-T Instruments: http://www.delta-t.co.uk/
Horiba-JobinYvon: http://www.jobinyvon.com/