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Technical Report TA User Project

Dicle Üniversity Smart Campus Project-DUSCP

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Abbreviations

DER	Distributed Energy Resource
DG	Distributed Generation
DSM	Demand Side Management
DR	Demand Response
MG	Microgrid
MPPT	Maximum Power Point Tracker
OPC	Open Platform Communications
P&O	Perturb and Observe
PV	Photovoltaics
RES	Renewable Energy Sources
TA	Trans-national Access

Executive Summary

This project deals with the operation analysis and evaluation of a 250kWp Photovoltaic System installed at Dicle University in Diyarbakir, South-eastern Turkey. The system, already in operation since November 2014, has been the test bed for knowledge gaining in the field of renewables and smart grid technologies. In this context, the specific TA project aims at evaluating the performance of the specific power plant under various operating scenarios. Overall, the objective of the analysis is to assess the efficiency of the existing system as well as to investigate methods of increasing its efficiency and reducing the impact on the local distribution grid, especially during peak-production intervals.

The project was planned and implemented in three phases which are presented below:
-Firstly, the system was analysed in terms of performance (energy yield) considering it as a stationary PV plant with the solar irradiance and ambient temperature data for one year as inputs to the system.
-In the second phase of the project, the system was modelled as a 2-axis tracking PV plant. This way, the plant achieves a significant increase in its energy yield. This configuration is tested for the same irradiance and ambient temperature input data as the stationary system.
-The third and most important part of the project regarded the performance analysis of a Demand-Side Management strategy in order to balance the PV production of the plant with the local consumption. This way, the impact of the PV plant on the voltage can be alleviated.

It is worth noting that in terms of laboratory implementation the project was implemented at CRES' DG-Lab and the tools used for the various phases/scenarios of the project were the following:
-Pure simulation using Matlab/Simulink for the performance evaluation of scenarios 1 and 2. The use of this approach was advantageous because it was possible to incorporate the real environmental data recorded at Dicle University between January and December, 2016, as well as to implement the real-scale model of the system, namely a model for a 250kW PV plant for both the stationary and the 2-axis tracking system.

-For the third scenario, a Real-Time Simulation approach was followed. Specifically, the setup involved the use of the CRES' experimental microgrid for the measurement of the environmental conditions (irradiance and ambient temperature). In addition, the actual resistive loads of the microgrid were used. In combination to the physical components a Matlab/Simulink model for the PV and the DSM controller were implemented. The model uses the input measurements by the microgrid and calculates in real time the output power of the PV. This power is used by the controller as a set-point for the resistive loads. Thus, our real-time simulation operates as a Simulation-in-the-Loop approach.

All in all, the results of the analysis show that the system's performance can significantly increase by using a 2-axis tracking system, whereas, for the DSM part of the project, the controlled load can satisfactorily follow the PV profile in order to obtain the required balance.

1 General Information of the User Project

The use of renewable energy sources is crucial to prevent climate change for the whole world. Turkey is a rich country with regard to renewable energy (solar and wind) potential. Especially, Turkey's South-eastern Anatolia Region which includes our research area Dicle University has a considerable potential in terms of solar energy. In the area where Dicle University campus is located, the average annual global radiation and the annual average sunshine duration are 1460 kWh/m^{2}year and 2993 hours/year, respectively. A photovoltaic solar power plant of 250 kWp has been installed within the campus and has been in operation since November 2014. The project team has gained experience in the design, installation and operation of power plants thanks to this power plant installation. This way, production data for Turkey's South-eastern Anatolia Region can be obtained under real operating conditions. Developing methods for eliminating the adverse effects of photovoltaic solar power plants on the power quality of the grid is an important research topic. Smart grid applications and energy management planning is another important research topic. Moreover, the effect of the photovoltaic power plant operated in the university campus on the power quality of the network needs to be investigated. In addition, a network management plan has to be made for the management of the new solar power plant planned to be built. Besides, different photovoltaic technologies should be tested in real climatic conditions and the most economical and efficient technology should be selected for the Diyarbakır province. Therefore, the aim of the project is to investigate the problems mentioned above.

This proposal was submitted in the frame of the first ERIGrid TA call as a collaborative project among three universities, namely Dicle Universitiy (Turkey), Batman University (Turkey) and Aalborg University (Denmark). The proposed hosting laboratories were apart from CRES' DG-Lab, AIT and IWES. The host organization was selected to be CRES. Also, the initial visit plan involved a 4-week visit in July 2017. Eventually, the visit of the researcher took place between 13/07/2017 and 04/08/2017.

2 Research Motivation

The energy issue has been always an important topic in the development of humankind. Domination of fire, using the wind for sailing or mechanical work, water mills, thermo-electrical power plants and nuclear energy are a few essential topics in the history which represent the evolution of the human being over a large period of time. Nowadays in the 21st century, the world is facing new challenges. Energy has become a priority, not only to meet the energy demands of industrial countries, but also to meet the energy demands of the increasing world population. Fossil fuels, with an overwhelming contribution to the world's energy supply, are expected to have limited reserves, threatening the future of the world's development at the present rate. Fossil fuels are also involved in atmosphere's pollution and associated to global warming.

To overcome these problems, before it ends in a crisis, man has focused on the development of new energy sources, which will represent the next step in human history. Among them, there is no doubt that the sun's energy, directly or indirectly, will play a main role in the future. In these days, photovoltaic systems directly collecting the sun's energy are increasingly being used and represent a growing trail of the solar industry and of the research in the scientific community. The improvement of the energy gain, via solar tracking systems, is one of the studied topics in this area.

The DSM technique is also an important issue in microgrids includes PV plants. Given the importance of the Smart grid concept towards building a sustainable electricity system, many innovative concepts have been proposed by researchers. Demand Side Management (DSM) is an important function that should be considered in the energy management of the smart grid system. It will support toward the functionalities of the smart grid in various areas such as electricity market control and management, infrastructure construction and management of decentralized energy resources. In a smart grid environment, economic operation means not only to economic scheduling of generation, but also to scheduling the load. In a Microgrid (MG), which comprises of intermittent Distributed Generators (DGs) (eg. solar and wind energy sources), the need of Demand Side Management (DSM)/ Demand Response (DR) becomes significant. The key point in DSM is to shift the load to some other point in time, this causes inconvenience to the customer and therefore it should be minimized. Minimizing the cost of generation and also minimizing the inconvenience caused due to shifting of loads is a multiobjective optimization problem.

2.1 Objectives

In the project the aim is to invastigate the performance of the 250kWp PV plant that is installed in Dicle University campus. The specific system is assumed as a stationary system, however, its performance as a 2-axis tacking system is also investigated. Last but not least, one of the most important topics addressed by this activity was the DSM of loads in order to match the PV production with the load consumption in order to achieve reduced energy dependency on the public utility energy as well as the impact of the PV operation on the grid's voltage. Overall, the project is divided into three scenarios, namely the evaluation of a 250kWp stationary PV system, the evaluation of the same power, 2-axis tracking system and the evaluation of a real time DSM for a micgrogrid that is installed in CRES, in Greece.

2.2 Scope

In this project the following tests were performed: evaluation of stationary and 2-axis tracker of a 250kWp Plant (with the operational characteristics of the real system installed at Dicle) and a real - time DSM simulation test. The PV plant tests were performed as pure simulation tests in Matlab/Simulink. In these tests solar mesurments acquired at Dicle University by means of a meterological measurerment station were used. These data included the global horizontal solar irradiance and the ambient temperature of the site where the actual PV system has been installed. Specifically, these tests were used to evaluate and compare a stationary version against a 2-axis tracking system of the 250kWp PV plant in terms of energy yield. Furthermore, for the DSM test the microgrid laboratory at CRES is used in combination with a Simulation-in-the-Loop model for the PVs and the controller. The scope of this test was to investigate the capability of the loads to follow in real-time the PV profile and, in addition, to evaluate the effectiveness of the specific test setup.

3 State-of-Technology

This project is focused on the performance of medium-scale, grid-connected PV plants and the effect of DSM implementation on microgrids. The renewable energy based production is very crucial for microgrids since RES are usually the main supplier of them. Therefore, and in order to ensure the microgrid's energy autonomy in the short or the long run the use of load control strategies is of utmost importance. Also, the impact of the PV production on a distribution grid plays a crucial role to the selection of the control strategies. Since this project aims at investigating a specific PV system at Dicle University, during the project it was important to investigate the effects of the PV plant on the Dicle University Campus distribution grid. Since this grid is planned to be operated as a microgrid in the near future, with the possibility of isolation from the public utility grid, it was important to investigate two main aspects of the system: The performance of the system in terms of power/energy yields as it is now configured and the improved performance in the case of upgrading the system to a 2-axis tracking PV plant. Last but not least, it was investigated how the DSM of loads could be used in order to effectively balance the production and consumption profiles, an important requirement for both the islanded and grid-connected operation modes.

The performance tests of the PV plant are divided into one test for a stationary and one for a 2-axis tracker 250kWp PV plant. As we will see in the following sections, to perform these tests we have used a Matlab/Simulink model of a PV system that takes into account the following components:
-One block that converts irradiance data from the horizontal level to the PV's plane as well as the temperature calculation of the PV's surface based on the ambient temperature and irradiance
-One block that calculates the I-V characteristic of one PV module based on the manufacturer's datasheet
-One block that performs the MPPT control of one module based on the P&O method
-One block that emulates the efficiency performance of a PV inverter based on its efficiency map data provided by the manufacturer

In addition to the abovementioned blocks, for the real-time DSM test we have also used:
-An extra block that calculates in real time the Direct Beam and Diffuse irradiance on a horizontal level using the measurements of the global horizontal irradiance in conjunction with data of actual date/time and geographical location of the system
-A block for controlling the loads of the microgrid based on the PV production
-Two OPC communication blocks used as ports for the exchange of data between the microgrid SCADA and the simulation model in real time. In the following sections all the above blocks are analytically described.

4 Executed Tests and Experiments

As mentioned in the previous sections during the activity three tests were executed: The first test regards the stationary, 250kWp, PV plant. This test aims to evaluate the performance of the plant on a yearly basis using real input data for the year 2016. Following this analysis, the researchers will use the derived results for comparison with the actual production of the system. The second test regards a 2-axis tracker, 250kWp, plant and it was used in order to assess the benefit of a potential upgrade of the system from a stationary to a solar position tracking system. Last but not least, the third and most important test regards the evaluation of a DSM strategy used in a microgrid by means of real-time simulation.

More analytically, in the first test the PV plant parts taken into account were the PV panels, the PV inverters which included an MPPT strategy, and an additional block for the input data conversion from horizontal to inclined level of the PV (irradiance and temperature). All these components are designed in Matlab/Simulink and they are analytically presented in section 4.3.

For the second test the same parts designed for the first test are used. Additionally, in order to incorporate the 2-axis tracking feature, the block that converts irradiance to the PV's plane is equipped with extra inputs representing the azimuth and inclination angles of the PV panels. In both tests the input data are fed to the model by means of a *.mat file which includes rows for time, direct horizontal irradiance, diffuse irradiance, ambient temperature and, in the second experiment, azimuth and inclination angles.

The third test regards the DSM control strategy. For this test we have used a combination of physical and simulated parts, in which the latter make up a Simulation-in-the-Loop configuration. Specifically, CRES' microgrid is used for the physical parts of the system as follows: the real horizontal irradiance and the ambient temperature are monitored in real-time with a sampling time of 1sec by means of sensors. The measurements are collected by the microgrid SCADA and they are communicated to the Matlab/Simulink computer by means of OPC. Within the simulation model, the irradiance data is converted to the actual direct and diffuse components for the site. These values, together with the ambient temperature are then used by another block that converts in real time the irradiance components from the horizontal level to the PV panel's plane. Also, the same block calculates the surface temperature of the model. The outputs of this block are again used by the PV block which calculates the actual current/voltage of one panel based on the set-point determined by the MPPT block. Eventually, the output power of the inverter is used as a set-point value for the loads. This signal is communicated back to the SCADA via OPC and the SCADA modifies the connectivity of the real microgrid loads in order to match the power of the simulated PV system. Overall, the objective is to investigate how accurately the PV profile is followed by the loads. The evaluation is based on specific indices described in the test results section.

4.1 Test Plan

The first part of the TA was dedicated to the implementation and execution of simulation tests for the stationary system. To this end, the input data for one year were divided into monthly data with a time resolution of 10 minutes. For each month of the year one separate test is conducted. Likewise, for the tracker system tests a similar approach with monthly tests was used. In addition to the input data used in test1, for this test the azimuth and inclination angles were included in each data file. This calculation for these two tests was performed manually prior to the test. Overall, the duration of each test for one month did not last more than 30 minutes, therefore, several repetitions of the same tests were conducted in order to investigate improvements to the models we have implemented.

The last group of tests that concerns DSM were real-time tests with duration of approximately 8 hours each. These tests were conducted for a smaller-scale PV system of 4.2kWp due to the fact that the matching loads of the CRES' microgrid is much lower than the 250kW of the actual PV plant. Also, by contrast to the first two tests, in this setup we have not used input data for the irradiance and temperature since these were provided by the microgrid in real time. Also, the model included the extra block for converting the global irradiance to the direct and diffuse components. Last but not least, the output of the controller was compared to the previous value and if there was a difference higher than 50W the set-point value sent to the microgrid SCADA was updated accordingly. This was selected in order to avoid continuous switchings of the microgrid's loads.

Finally, it is worth noting that during the 3.5 weeks of the activity the three experiments were not conducted in a specific order but their execution depended on the availability of the infrastructure and modifications in the various models.

4.2 Standards, Procedures, and Methodology

For setting up the various model components the following methodology and procedures were used:
PV panels: The first and foremost part of the tests is the model for emulating the behaviour of PV panels. Among various models for modelling the I-V characteristic of PVs the interpolated model [1] was selected. In this approach, the current or the voltage of a symmetrically operated PV module is described by the following equation set:

$$I = I_{SC}\left[1 - C_1\left(exp\left(\frac{V_R}{C_2 V_{oc}}\right) - 1\right)\right] + D_I \quad (1)$$

$$V = C_2 V_{oc} ln\left(\frac{1-(I-D_I)/I_{sc}}{C_1} + 1\right) - C_{TV}\left(T - T_{ref}\right) - R_S D_I \quad (2)$$

where:

$$C_1 = \left(1 - \frac{I_{mp}}{I_{sc}}\right) exp\left(-\frac{V_{mp}}{C_2 V_{oc}}\right) \quad (3)$$

$$C_2 = \left(\frac{V_{mp}}{V_{oc}} - 1\right) \Big/ ln\left(1 - \frac{I_{mp}}{I_{sc}}\right) \quad (4)$$

$$D_I = C_{TI}\frac{G}{1000}\left(T - T_{ref}\right) + I_{sc}\left(\frac{G}{1000} - 1\right) \quad (5)$$

$$V_R = V + C_{TV}\left(T - T_{ref}\right) + R_S D_I \quad (6)$$

MPPT algorithm: The method used for implementing the specific block was the P&O method [2]. This algorithm is the most commonly used method in PV inverters and is based on the perturbation of the voltage and the observation of the resulting power deviation. Depending on the change of power the algorithm infers if the system moves to or away from the maximum point of operation. In the following figures (Figure 1 and Figure 2) the operating principle of the P&O method together with the flowchart implementation diagram are shown.

PV inverter: The model selected and used for the PV inverters of the system takes into account the energy efficiency of the inverter only. In this respect, the model used for the inverter efficiency was a lookup table with two input signals, such as the DC voltage and the input power. Based on the combination of the two inputs one efficiency value is selected from the table and multiplied by the input power in order to calculate the power injected to the AC grid. The specific implementation is shown in section 4.3.

Calculation of plane irradiance and PV surface temperature: For the conversion of the horizontal level irradiance data to the plane irradiance, the following mathematical formulation was used [3]:

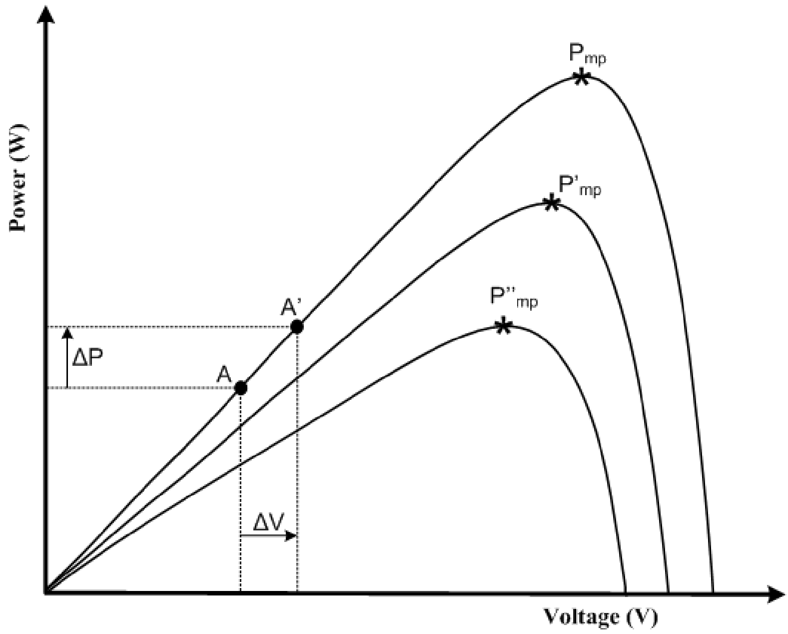

Figure 1 Operating principle of the implemented P&O method

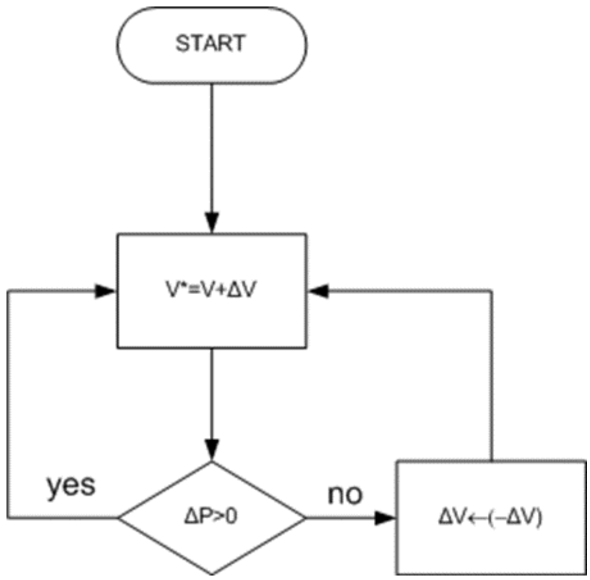

Figure 2 Flowchart of the implemented P&O method

$$\Gamma = \frac{2\pi(d_n - 1)}{365} \tag{7}$$

Where Γ is the day angle in radians, and d_n is the day number of the year ranging from 1 for January 1st to 365 for December 31st.

$$\delta = sin^{-1}\left(sin\left(\frac{23.442\pi}{180^o}\right)sin(4.901 + 0.033sin(-0.031 + \Gamma) + \Gamma)\right) \tag{8}$$

Where δ is the solar declination angle.

$$E_t = \frac{4\pi}{180^o} tan^{-1}\left(\frac{tan(4.901+\Gamma) - cos\left(\frac{23.442\pi}{180^o}\right) tan(4.901 + 0.033sin(-0.031+\Gamma)+\Gamma)}{tan(4.901+\Gamma)cos\left(\frac{23.442\pi}{180^o}\right) tan(4.901 + 0.033sin(-0.031+\Gamma)+\Gamma)+1}\right) \tag{9}$$

$$LAT = LST + E_t + 4(L_s - L_e) \tag{10}$$

Where E_t is the equation of time, LAT is the Local Apparent Time, LST is the Local Standard Time, L_s is the standard longitude and L_e is the local longitude for the place of calculation. Based on the above equations, the solar altitude is calculated as follows:

$$sina = sin(\delta)sin(\varphi) + cos(\delta)\cos(\varphi)\, cos(\omega) \tag{11}$$

Where α is the solar altitude, φ is the geographical latitude in degrees (north positive), and ω is the hour angle (noon zero and morning positive). Eventually, the diffuse irradiance on the inclined surface is calculated by the formula:

$$E_{diff} = D_h \left(0.5\big(1 + cos(beta)\big)\right) A \tag{12}$$

Where D_h is the diffuse irradiance on horizontal level, beta is the inclination angle of the PV panel, and A a coefficient that is calculated based on the model in [4]. Similarly, the direct irradiance on the inclined surface is calculated as follows:

$$E_{direct} = E_n(cos(sin^{-1}a)cos|g|sinbeta + sinacosbeta) \tag{13}$$

$$|g| = cos^{-1}\left(\frac{sinasinL_e - sin\delta}{cosacosL_e}\right) \tag{14}$$

Where, E_n is the direct normal irradiance on the horizontal surface. Finally, the total irradiance on the inclined surface is calculated as the sum of the diffuse and the direct components by adding a reflection component E_g as follows:

$$E_{tot} = E_1 + E_2 + E_g \tag{15}$$

$$E_g = \frac{1}{2} g_{ref}(1 - cosbeta)(D_h + E_n sina) \tag{16}$$

With g_{ref}=0.2. Last but not least, the surface temperature is calculated by the combination of the ambient temperature ($T_{amb.}$) and the total irradiance on the PV as follows:

$$T_{surf.} = T_{amb.} + 0.05E_{tot} \quad (17)$$

<u>Calculation of direct and diffuse from global horizontal irradiance</u>: Due to the fact that the input irradiance data in all tests consists of the global horizontal value, an extra calculation block that converts the specific value to the corresponding direct and diffuse components was implemented. This block makes use of the following calculation for the diffuse irradiance [3]:

$$\frac{I_d}{I} = \begin{cases} 1 - 0.09M_T, & 0 \leq M_T \leq 0.22 \\ 0.9511 - 0.1604M_T + 4.388M_T^2 - 16.638M_T^3 + 12.336M_T^4, & 0.22 \leq M_T \leq 0.80 \\ 0.165, & 0.80 \leq M_T \end{cases} \quad (18)$$

$$M_T = \frac{I}{I_0} \quad (19)$$

Where I is the global horizontal irradiance and I_0 is calculated by the formula:

$$I_0 = I_{SC}E_0(sin\delta sin\varphi + cos\delta cos\varphi cos\omega) \quad (20)$$

Where I_{SC}=1367W/m^2, and E_0 is the eccentricity correction factor given by:

$$E_0 = 1 + 0.33cos\left(\frac{2\pi d_n}{365}\right) \quad (21)$$

4.3 Test Set-up(s)

<u>Test 1</u>: The diagram of Figure 1Figure 3 provides an illustration of the block selected for the specific test. The main blocks that we can distinguish in this implementation are: the input file block used for reading the irradiance and temperature data, the horizontal to the inclined surface block which calculates the irradiance on the PV plane as well as the surface temperature, the I-V model of the PVs which calculates the current which is fed to the MPPT block and receives as input the DC voltage from the latter, the MPPT block which tracks the maximum power for the selected conditions, and which communicates this value to the inverter efficiency's model, and, finally, the inverter's efficiency block which converts the DC power to the corresponding AC value.

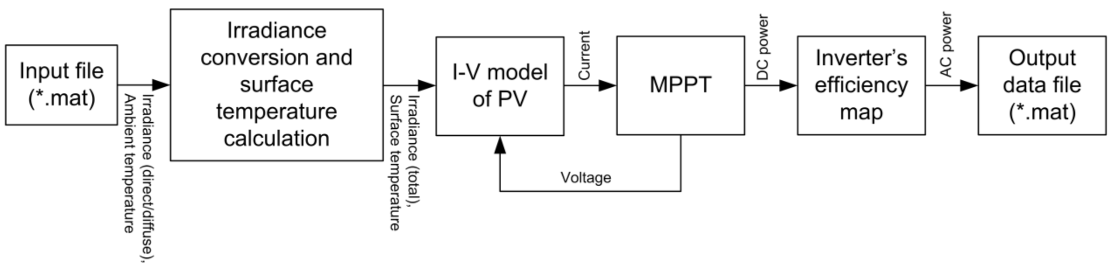

Figure 3 Implementation block diagram for Test no 1

In addition to the above generic diagram, the corresponding Matlab/Simulink implementation is shown in Figure 4. Also, apart from the complete implementation model other important blocks of the implementation are depicted in the following figures: Figure 5 illustrates the Simulink model of the PV panels, Figure 6 illustrates the MPPT implementation, Figure 7 illustrates the efficiency map implementation, and Figure 8 illustrates the conversion from the horizontal to the tilted surface Simulink model. It is worth noting that these subsystems are also used in the tests 2 and 3.

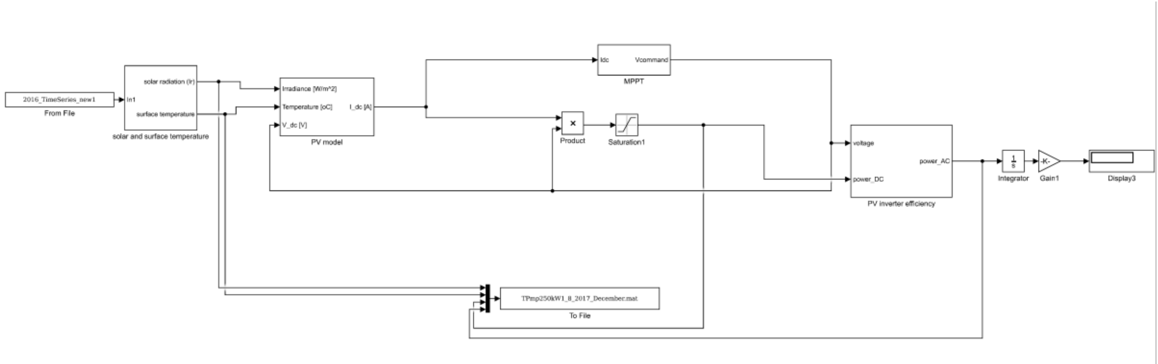

Figure 4 Simulink block diagram for the stationary PV system test-Test1

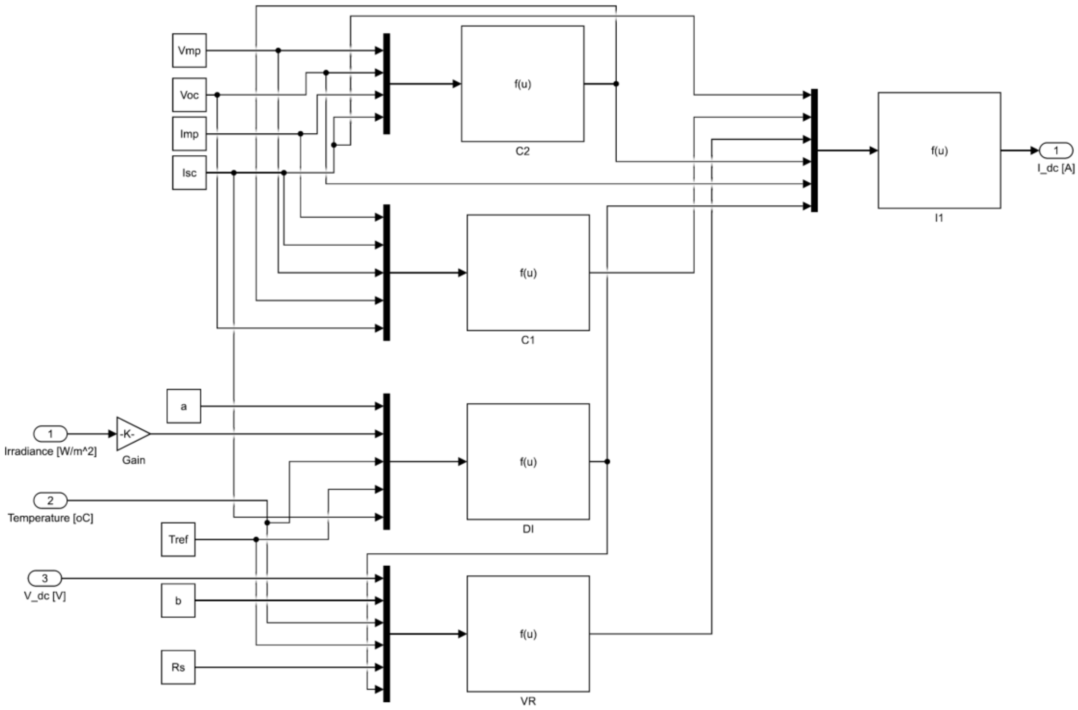

Figure 5 PV model Simulink implementation

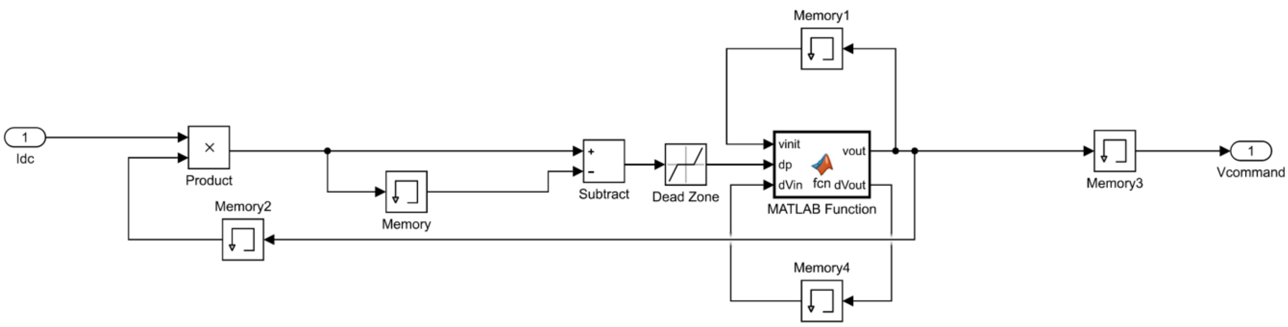

Figure 6 MPPT model's implementation in Simulink

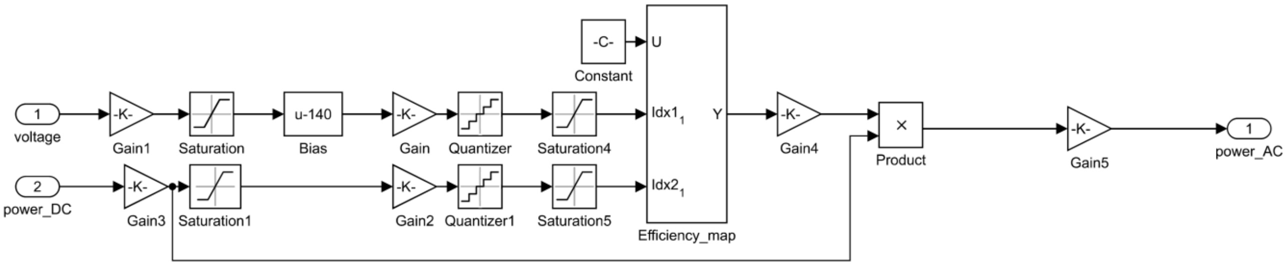

Figure 7 Inverter's efficiency model implementation in Simulink

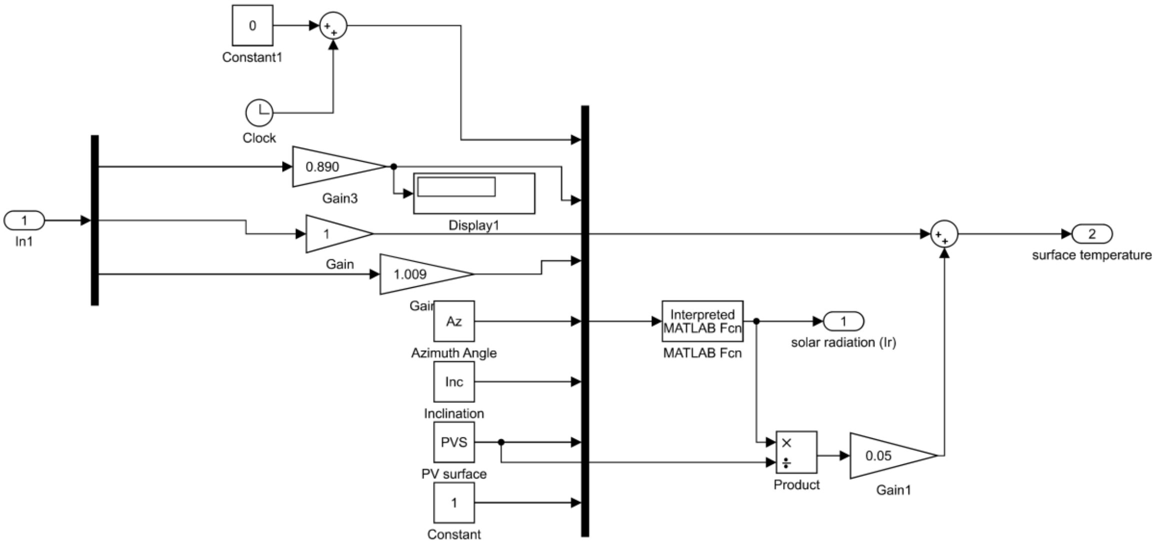

Figure 8 Horizontal to inclined irradiance and surface temperature calculation in Simulink

Test 2: For the second test the generic setup of Figure 9 is used. Essentially, this setup is almost identical to the Test1's setup, with the only difference being the additional input to the Irradiance conversion function block. This block, initially designed for fixed inclination and azimuth angles of the PV, has slightly been modified to receive as extra inputs the two angles from a separate *.mat file. This way, the orientation of the PV panels is modified following the sun's position and as a result the overall energy yield of the system increases. Additionally, Figure 10 shows the Simulink implementation of the specific test.

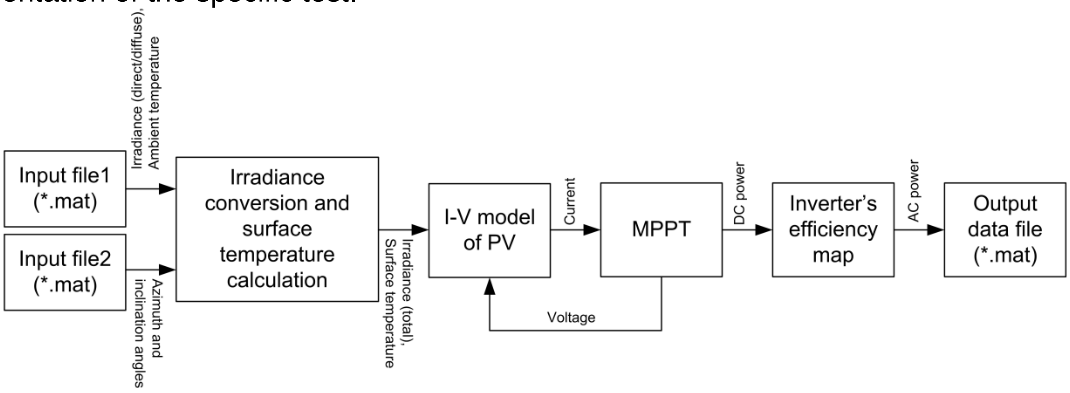

Figure 9 Implementation block diagram for Test no 2

Test 3: Last but not least, the specific (real-time) test was implemented based on the diagrams shown below (Figure 11 and Figure 12). The diagram in Figure 11 shows the hardware setup for the specific experiment. This configuration includes the following parts of the microgrid:

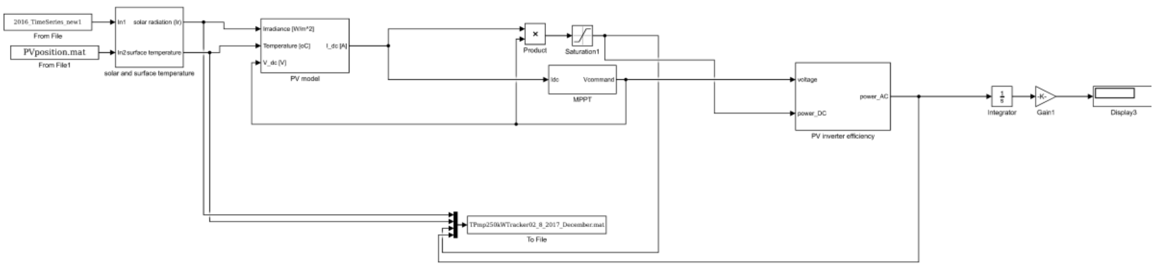

Figure 10 Simulink block diagram for the 2-axis tracking PV system test-Test2

-One AC source, namely the AC LV grid of CRES
-One breaker which connects the microgrid to the public utility
-One line segment for the connection of loads to the microgrid
-One busbar upon which loads and transducers are connected
-One automated load bank consisting of resistive loads (4.5kW per phase)
-One active power transducer for monitoring and recording the actual load power
-One irradiance sensored positioned on a horizontal level
-One ambient temperature sensor
-Three Interbus Analog Input modules for the signals' monitoring
-One Interbus Digital Output module for the load control
-The microgrid's SCADA system
-One computer used as the real-time simulator

Regarding the latter, the analytical block diagram in Figure 12 shows the blocks used for the implementation. The simulink implementation of the test is shown in Figure 13. Also, the implementation of the global to direct and diffuse irradiance calculation is shown in Figure 14. Finally, the implementation of the specific test requires the real time calculation of LST. This is done by means of the model of Figure 15.

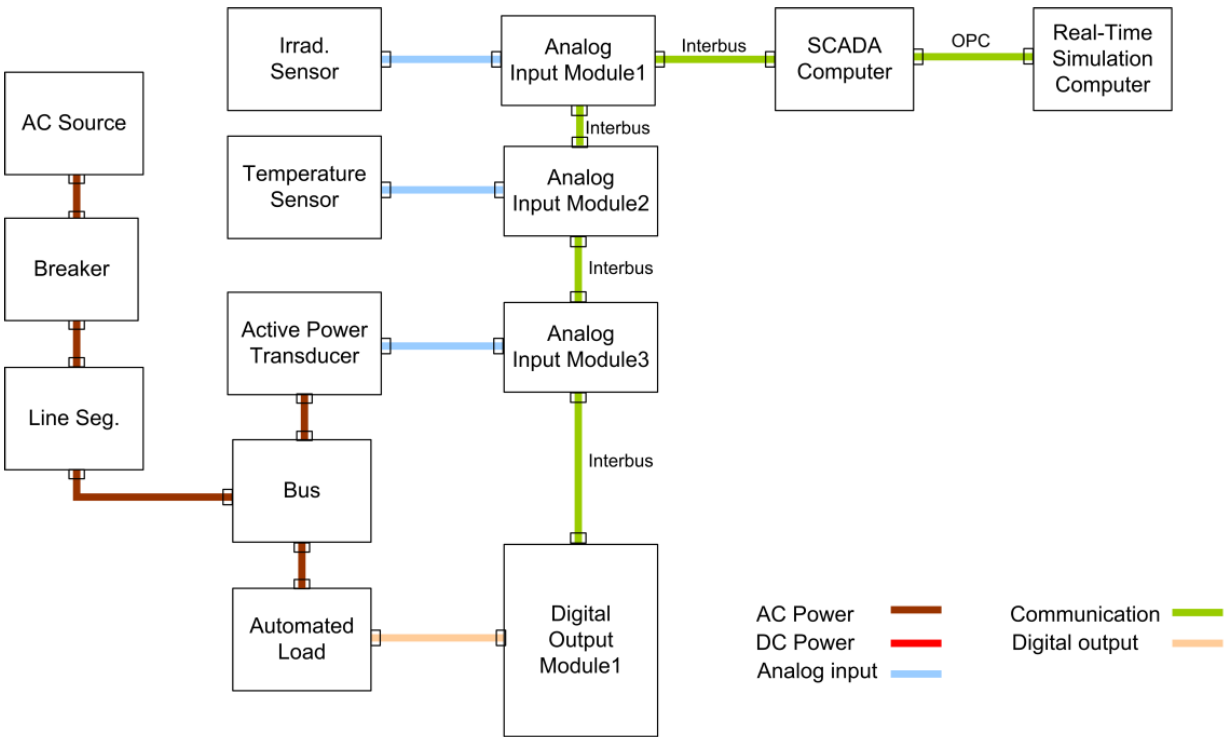

Figure 11 Test3 experimental setup showing the hardware interconnections

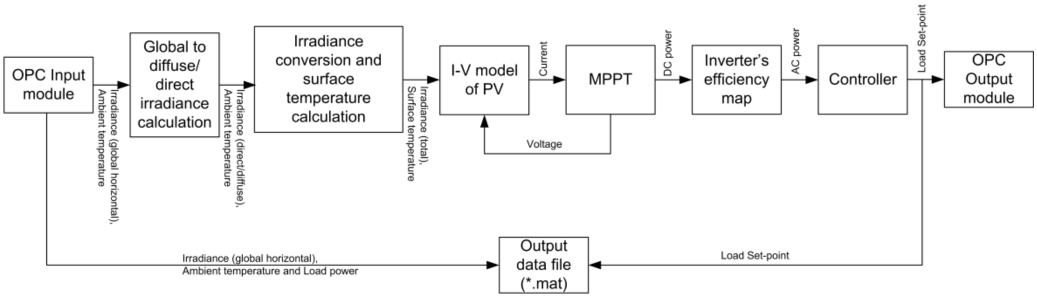

Figure 12 Implementation block diagram for Test no 3 (Simulation part only)

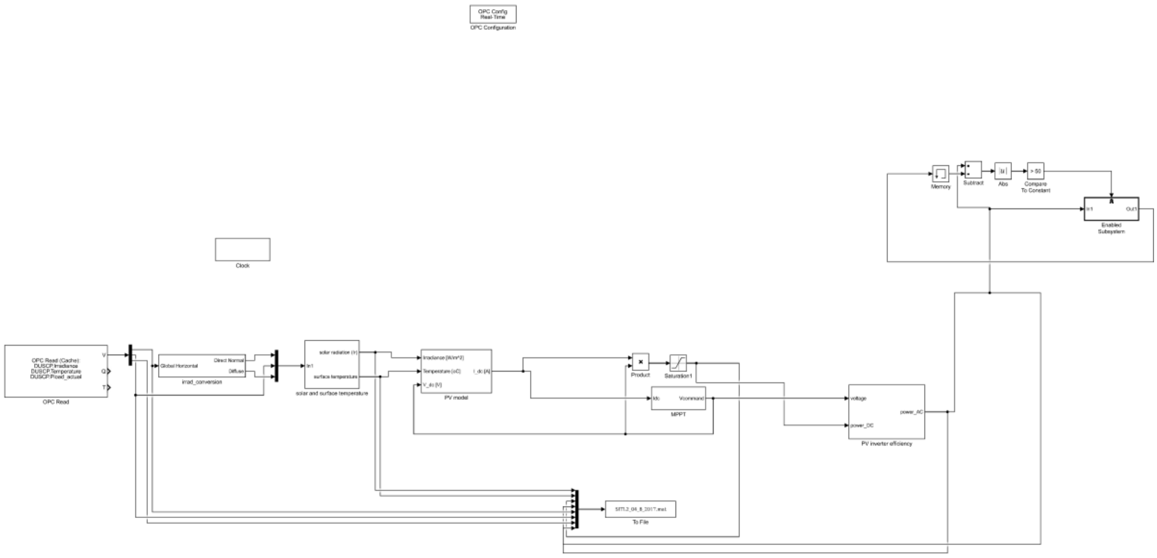

Figure 13 Simulink block diagram for the real-time simulation test-Tes3

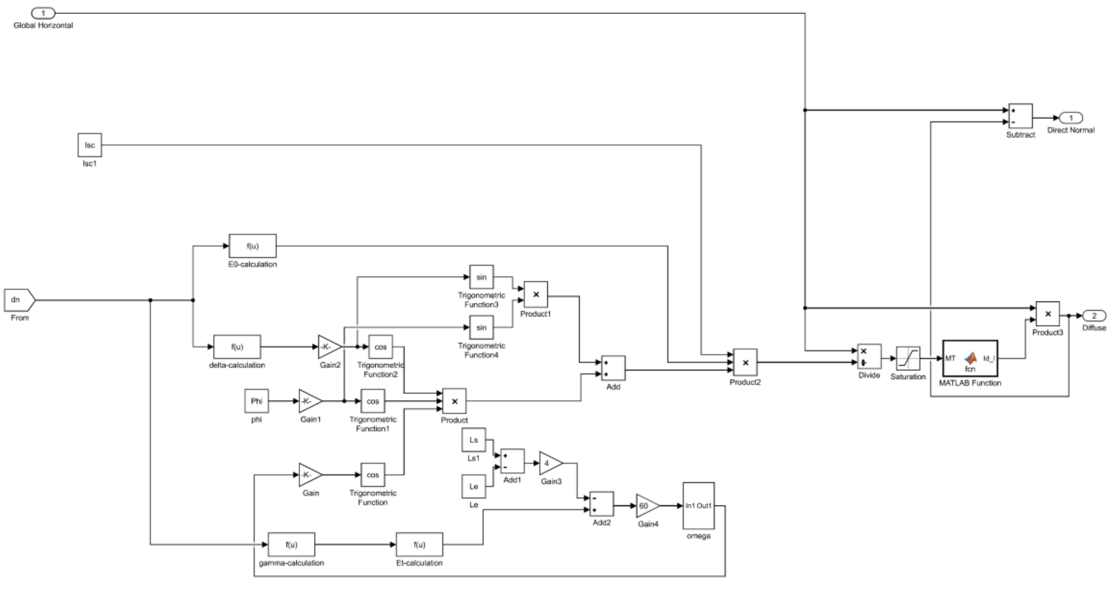

Figure 14 Simulink implementation of the conversion from global to direct and diffuse irradiance

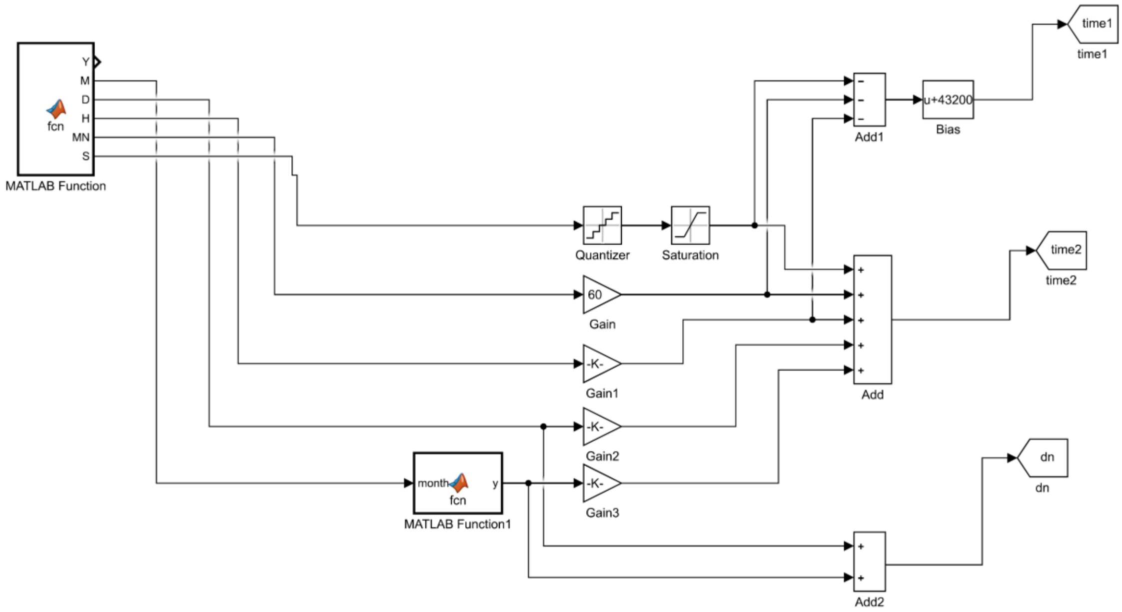

Figure 15 Calculation of LST as the time in seconds elapsed from January 1st

4.4 Data Management and Processing

As it is shown above the input data are inserted to the models via 'from_file' Simulink blocks. Specifically, the input data have had the form of *.mat files. In addition, the same principle of data management is used for the recorded (output) data. Each test includes an output *.mat file corresponding to the name of the setup, the date of implementation, and the scenario which this test refers to (e.g. 'TPmp250kWTracker26_7_2017_September.mat'). The input files are introduced to the model after being manually processed and prepared in excel. The format of the input excel file is an array that contains columns of each of the input parameters (direct irradiance, diffuse irradiance, ambient temperature, azimuth angle, inclination and time) with a time resolution of 10 minutes. The corresponding *.mat files contain the same data transposed so that each column becomes a row. Similarly, the output *.mat files contain each variable in a separate row together with time. For the analytical recording of all parameters, the quantities recorded and stored are the: solar irradiance on the PV plane, surface temperature, DC and AC power, real global irradiance, real ambient temperature, set-point of loads and actual power of loads. The output data can be further processed in Matlab or Excel.

5 Results and Conclusions

The performance of the stationary and the 2-axis tracker system are compared to each other in terms of DC output of one PV module and total AC output power. The analytical power output for each month is depicted in Figure 16 and Figure 17 respectively. Furthermore, the two setups are compared in terms of monthly energy yield. The results of this comparison are summarized in Table 1. It is worth noting that the variation in the PV's orientation can significantly increase the energy yield of the system by 35% in July (highest increase) or by 20% in December (lowest increase).

Table 1 Monthly energy production of the stationary and the 2-axis tracker 250kWp PV system

Month	***Stationary (kWh)***	***Tracker (kWh)***	***Increase (%)***
January	11460	14180	23.73
February	17040	20790	22.01
March	25600	31390	22.62
April	33540	41900	24.93
May	36230	46490	28.32
June	36630	48650	32.81
July	38820	52300	34.72
August	33890	43720	29.01
September	30900	38610	24.95
October	23890	29660	24.15
November	17230	21640	25.59
December	10870	13060	20.15

In addition to the above data the PV surface temperature and the corresponding irradiance for each month are also shown in Figure 18 and Figure 19 respectively. These data provide an overview of the operating conditions for the PV system.

On the other hand, the main results from Test3 (DSM control) are shown in Figure 20-Figure 23. More analytically, Figure 20 shows the actual load profile compared to the simulated PV production (AC power). As it is evident from this diagram, the loads follow the PV production with a satisfactory accuracy. The power accuracy in the load profiles is always under 25% (with the exception of the initial values before the load activation which due to zero load consumption is 100%). The diagram in Figure 24 shows the variation of this deviation over time. Furthermore, in terms of energy, the difference between the PV yield and the load consumption is calculated to -4.867%. Overall, the two test criteria show that the system achieves the desired target metrics which are 25% peak power deviation and 10% energy deviation.

In addition to the power profiles, some other data are also depicted in Figure 21 (Global Horizontal versus PV surface irradiance), Figure 22 (PV surface temperature), and Figure 23 (DC output power of one PV module).

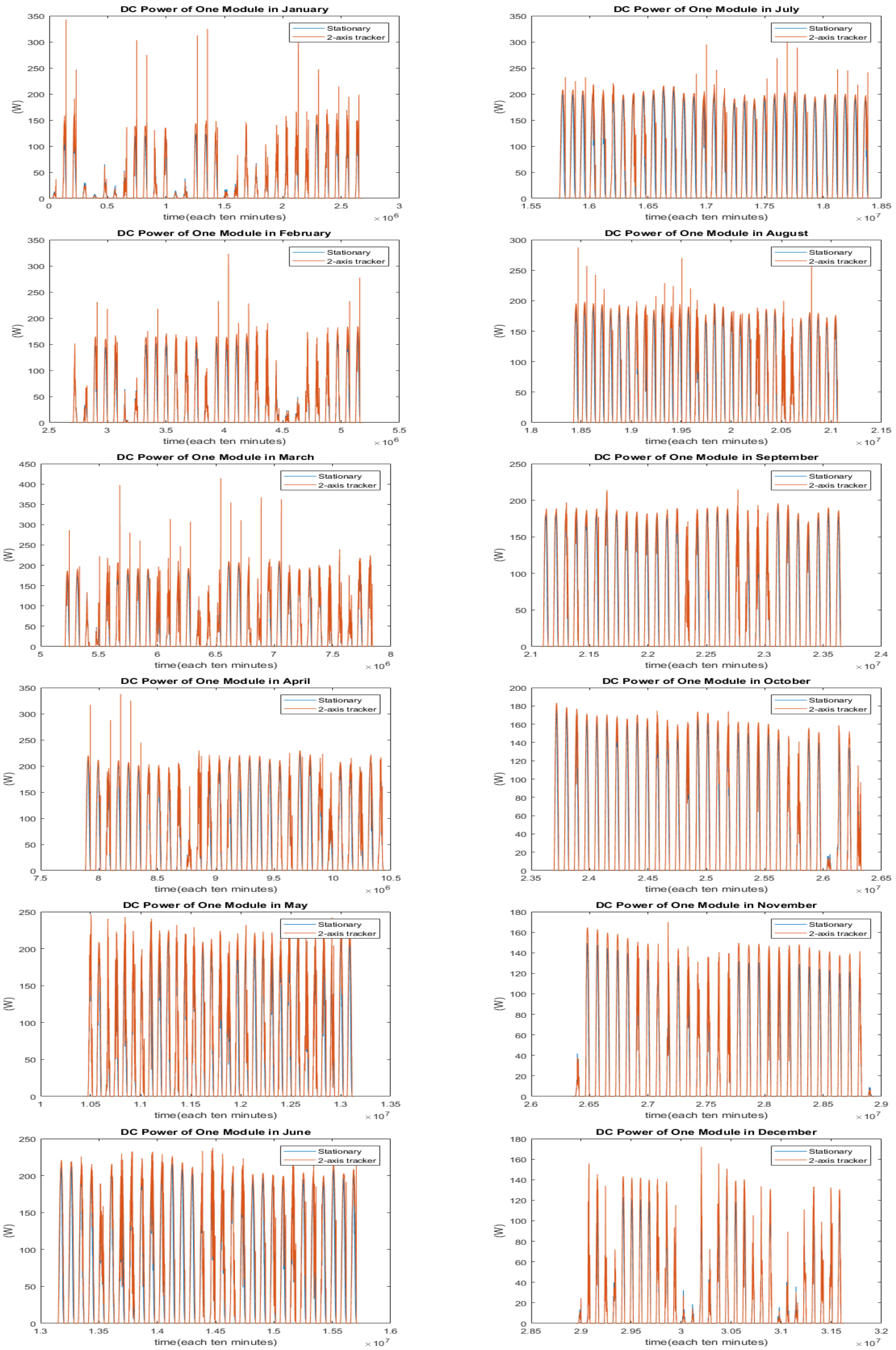

Figure 16 Test results of DC power for the stationary and the 2-axis tracker

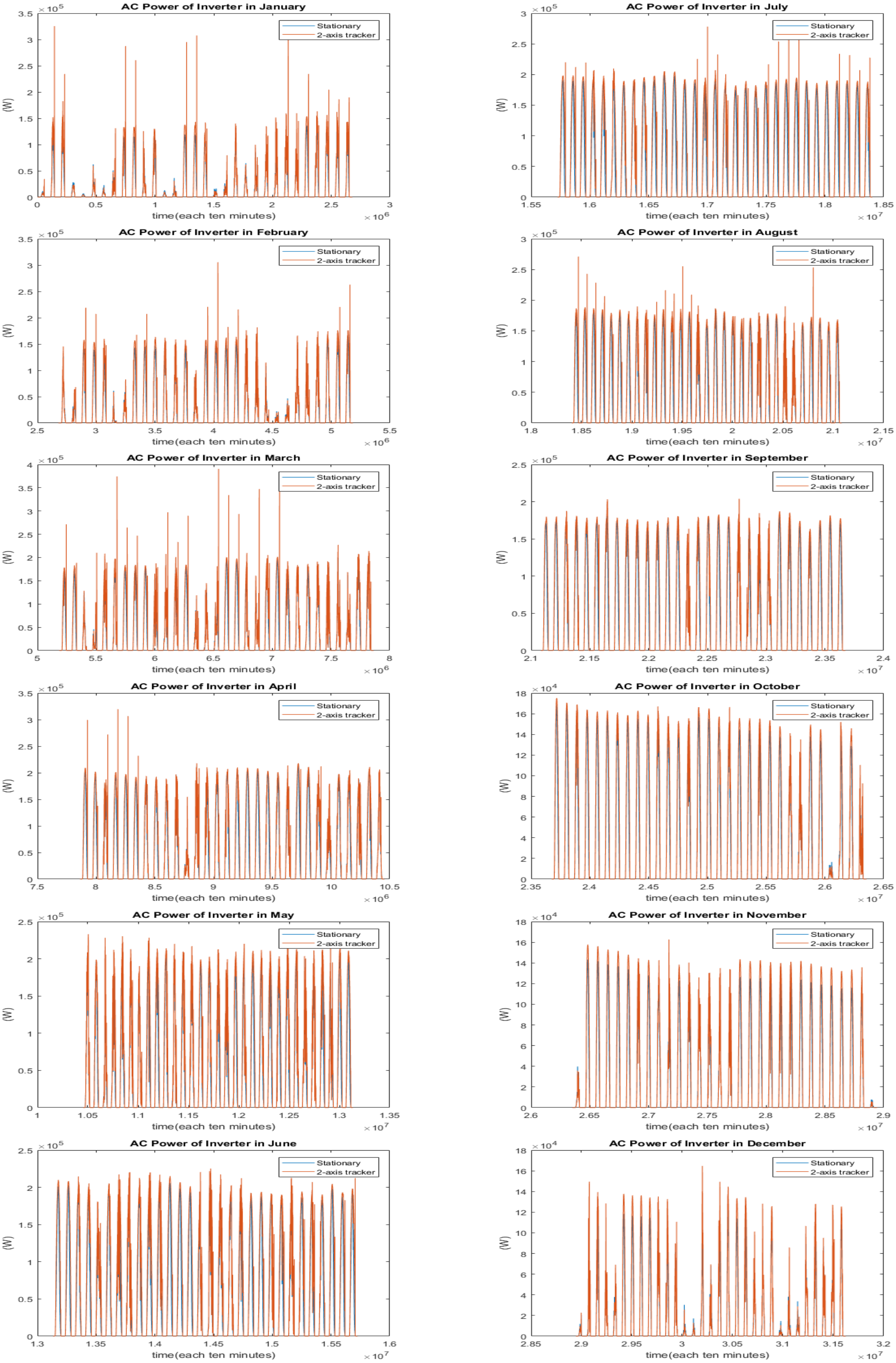

Figure 17 AC power for the stationary and the 2-axis tracker

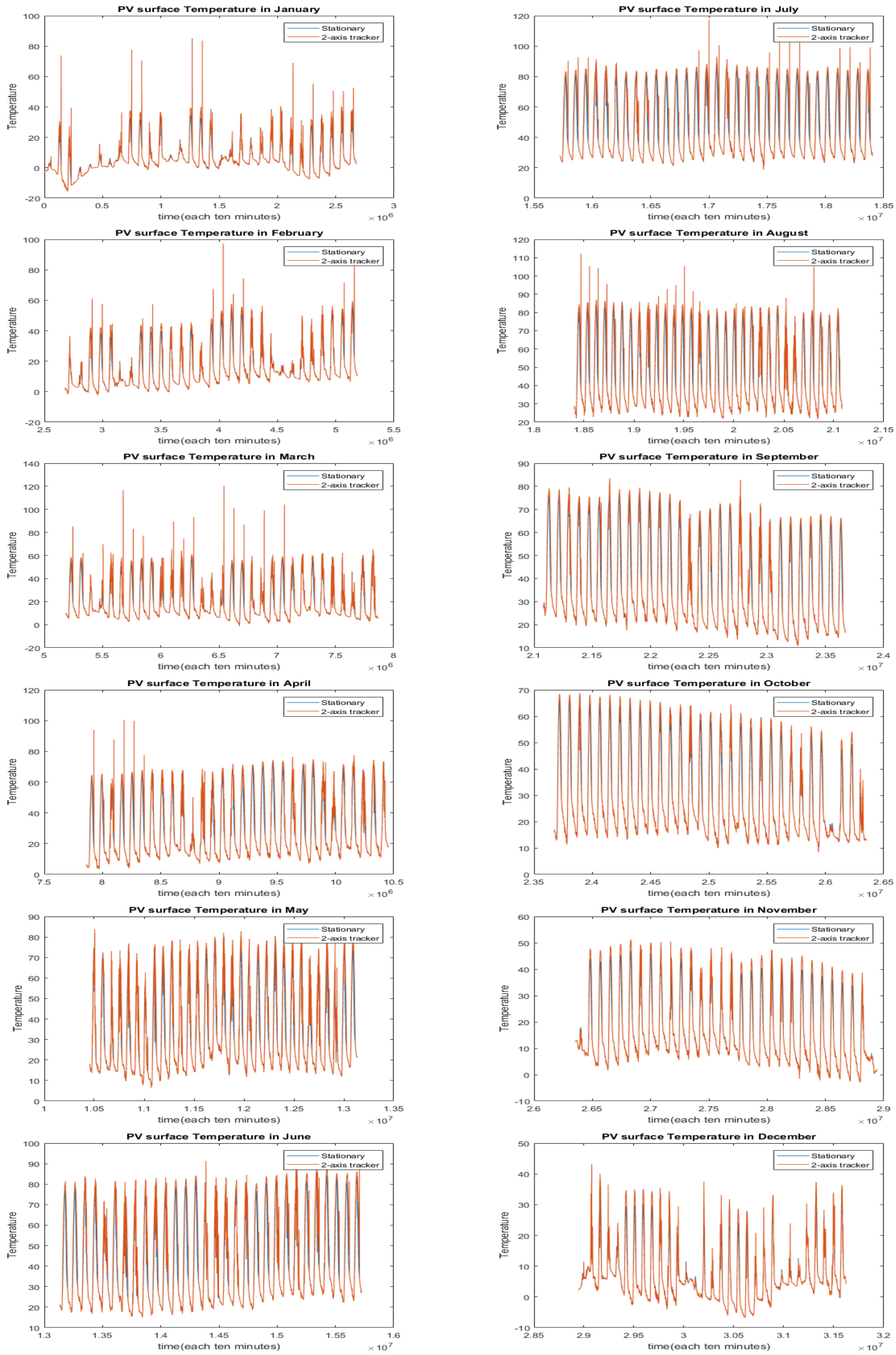

Figure 18 PV surface temperature

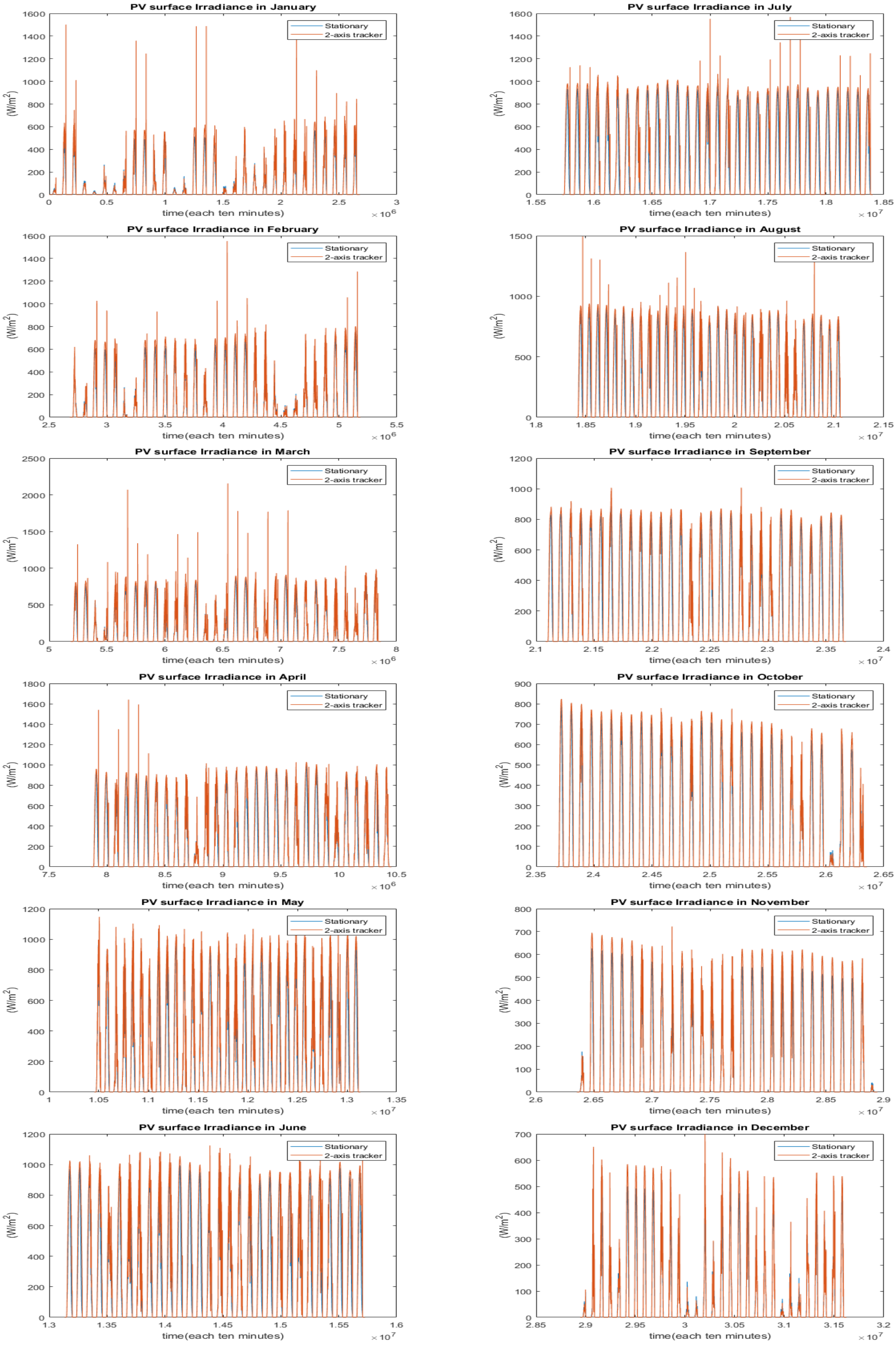

Figure 19 PV surface irradiance

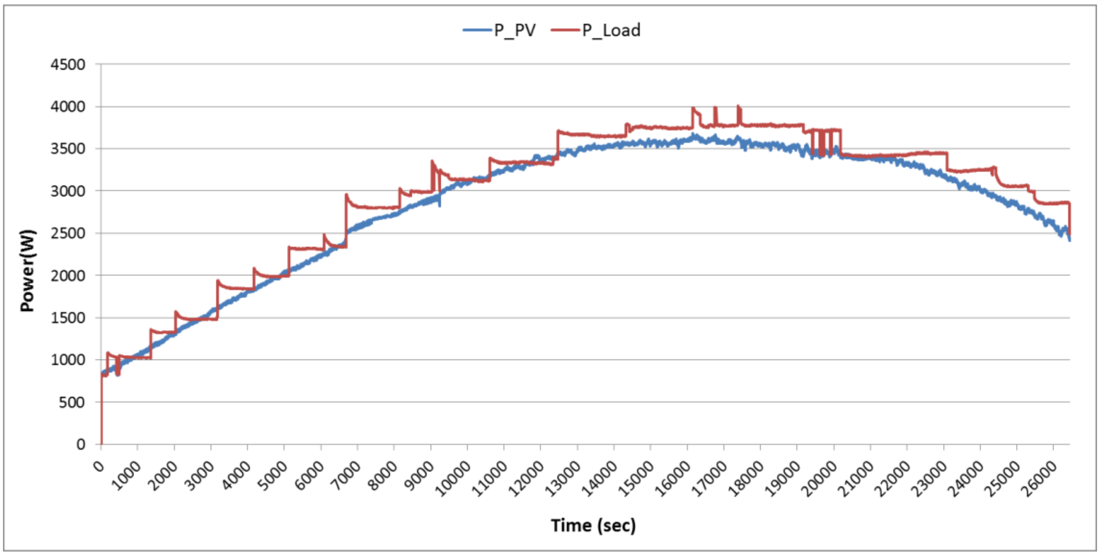

Figure 20 Comparison of actual load and PV production profile

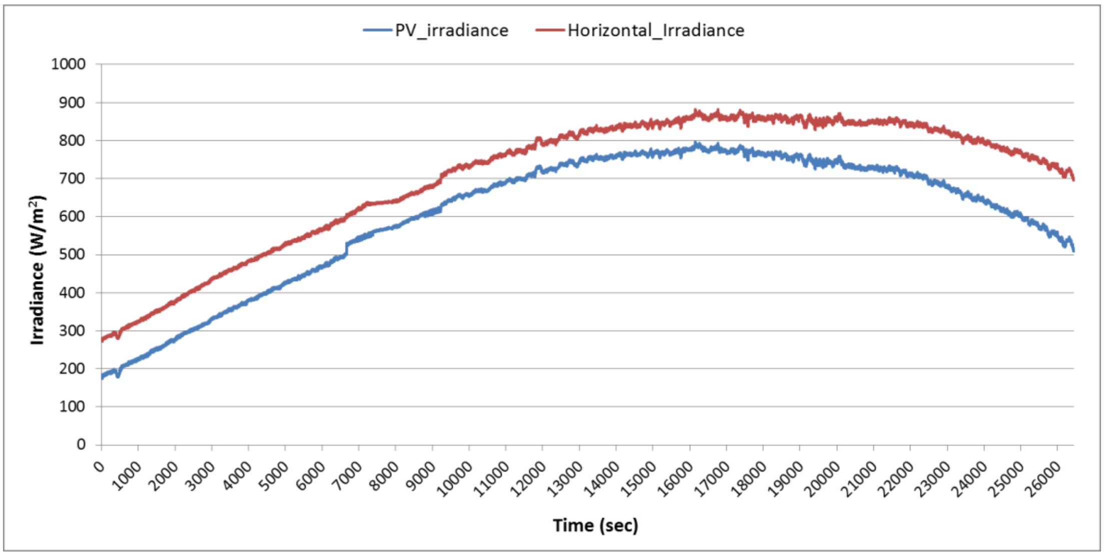

Figure 21 PV surface irradiance and Global Horizontal irradiance

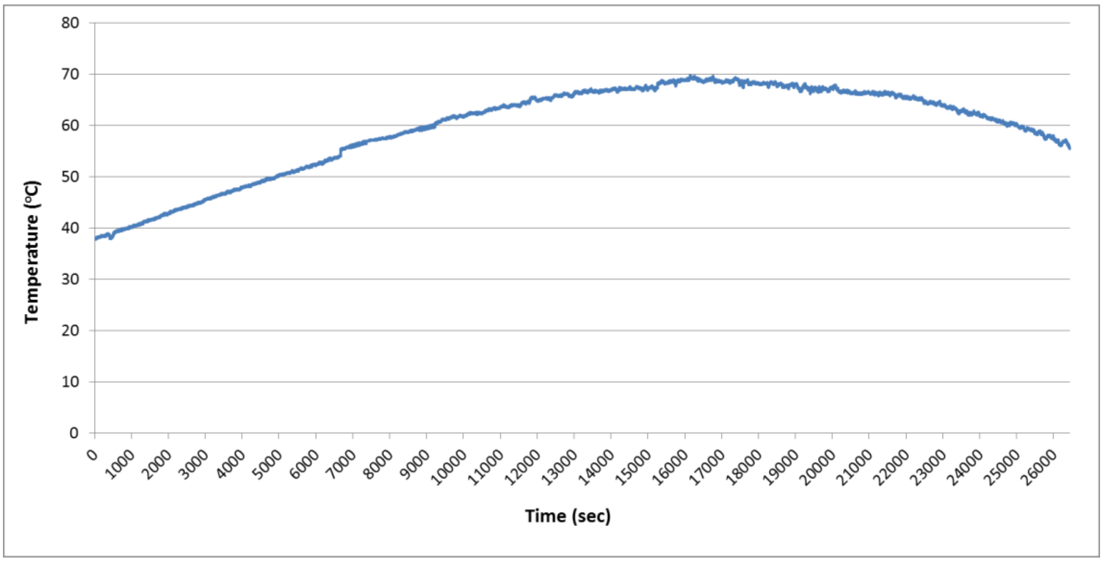

Figure 22 PV surface temperature

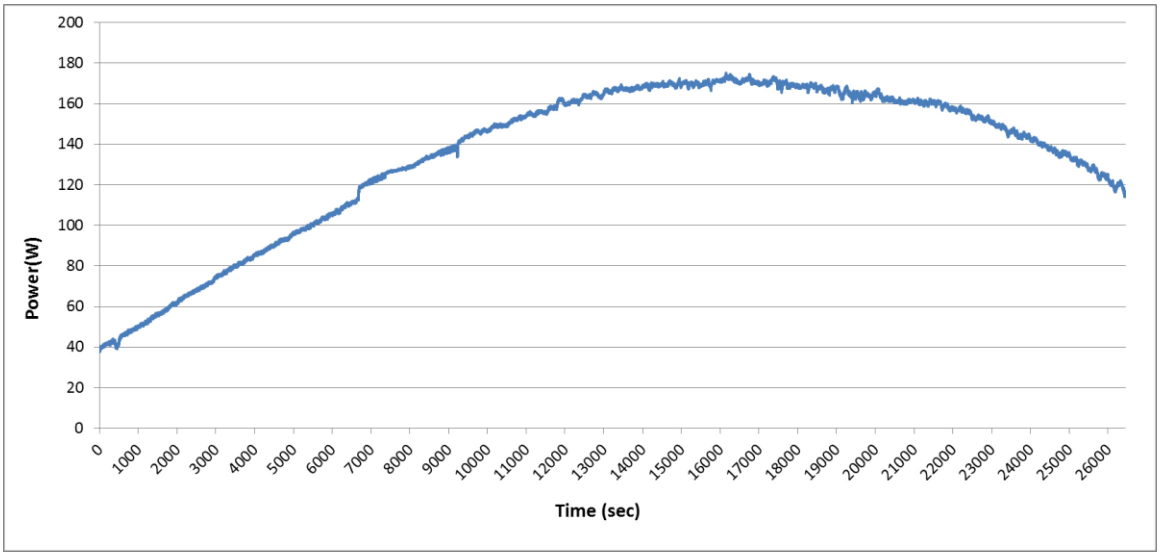

Figure 23 DC output power for one PV Module

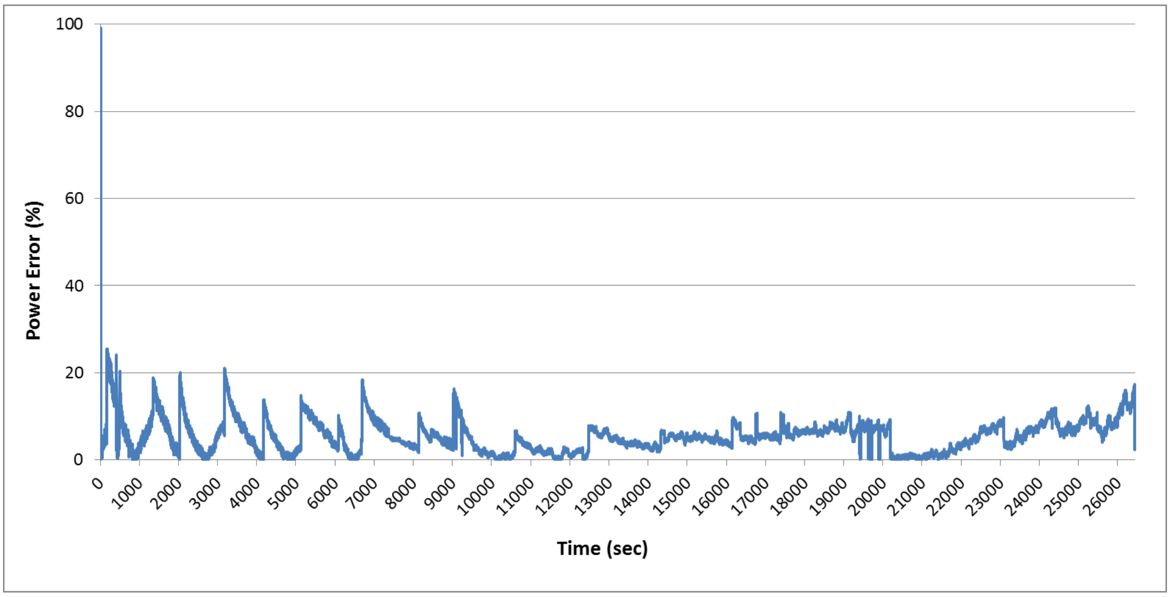

Figure 24 Deviation of power between PV production and load production

6 Open Issues and Suggestions for Improvements

From a technical point of view some of the potential improvements of the specific tests concern the following topics:

-The ambient temperature measurement in Test3 was conducted by means of a PT1000 sensor connected to the Lead-Acid battery storage. The latter system was not in operation in order to avoid inaccuracies in the measured temperature. Even still, the measured temperature was not accurate enough because the variations of the batteries temperature were rather smoother than the actual ambient temperature. Also, due to the fact that this measurement was conducted by the battery inverter, there was limited accuracy in the decimal places of the measurement value. Because of that, for future implementations we have replaced the specific measurement with an outdoor temperature sensor (PT1000) which provides a more precise measurement of the ambient temperature directly monitored by the SCADA system.

-The model for converting the horizontal to the PV plane irradiance presents some inaccuracies at the end of each day in the diffuse irradiance calculation and, in particular, when a tracker is assumed. These inaccuracies lead to some spikes of the PV production, which due to their short duration do not influence the energy yield of the experiment. This model is being processed in order to improve its accuracy for future tests.

-The control used for the loads was essentially an open-loop approach in which the set-point is fed to the SCADA system and the SCADA system selects a resistors' combination to satisfy this set-point. In future implementations, the Matlab/Simulink model will include a closed-loop controller which, based on the power load feedback, will correct any discrepancies from the set-point.

7 Dissemination Planning

The dissemination plan of the DUSCP project includes submission of two conference papers. One paper will regard pure simulation and it will be submitted to the “International Engineering Conference (IEC 2017, Antalya, Turkey)”. The other paper that regards real-time simulation will be submitted to the “2018 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)”.

In addition, the paper that regards real-time simulation will be submitted to the “Simulation Modelling Practice and Theory” journal.

8 References

[1] K. Khouzam und K. Hoffman, „Real-Time Simulation of Photovoltaic Modules," *Solar Energy, Vol. 56, No. 6,* pp. 521-526, 1996.

[2] D. P. Hohm und M. E. Ropp, „Comparative study of Maximum Power Point Tracking Algorithms," *Progr. Photovolt: Res. Appl., Vol. 11,* pp. 47-62, 2003.

[3] M. Iqbal, An introduction to solar radiation, Don Mills, Ontario: Academic Press Canada, 1983.

[4] R. Perez, R. Seals, P. Ineichen, R. Steward und D. Menicucci, „A new simplified version of the Perez diffuse irradiance model for tilted surfaces," *Solar Energy, Vol. 39, No. 3,* pp. 221-231, 1987.

9 Annex

9.1 List of Figures

9.2 List of Tables