PREDICTIVE CONTROL STRATEGY FOR STAND ALONE PV HYBRID SYSTEMS USING EUROPEAN INSTALLATION BUS (EIB).

T. Romanos, S. Tselepis, G.Goulas
Centre for Renewable Energy Sources,
19th km. Marathonos Ave., GR-190 09, Pikermi, Greece,
Tel. +301 6039 900,
Fax +301 6039 905,
E-mail : troman@cres.gr

ABSTRACT: The paper focuses on the design and development of a Predictive Control System for stand alone PV Hybrid Systems using the European Installation Bus (E.I.B.). This work was partly performed during the course of realization of two JOULE projects (JOR3-CT97-0158 and JOR3-CT98-0244).
The Control System minimizes the production costs through an on-line optimal scheduling of the power units, taking into account the technical constraints according to the State Of Charge (S.O.C.) of the battery Bank, as well as forecasts of the load and the Photovoltaic energy contribution several hours ahead.
Keywords: Stand-alone PV Systems –1: Hybrid – 2: Expert System - 3

1. PREDICTIVE CONTROL FOR STAND ALONE HYBRID SYSTEMS

A Control Strategy for Hybrid Systems is being developed, based on k-step ahead control horizon coupled with on-line system identification procedures.

The Hybrid System may consist of a Diesel generator unit, a Photovoltaic generator unit, a battery inverter and a load simulator for a typical small Greek island. The Diesel generator model is based on a typical deterministic linear model.

The estimation of the PV contribution, depending on the PV penetration phase, can be decided arbitrarily and it corresponds on an average day of a month in the Aegean Islands. A deterministic model has been developed for the state of charge (SOC) of the battery bank. A representative deterministic model can be used for the simulation of a two way battery inverter. Linear parametric models, like ARMAX model, can be derived for simulation, using data from load simulator correlated with the data of the PV inverter.

Predictive control strategy is developed for stand-alone Hybrid Systems. The advantage of predictive controllers is that they are relative easy to tune. They can be derived for and applied to multi-input, multi-output (MIMO) processes. That means that they can be adapted to the principles of the PV-hybrid's concept. Predictive controllers can also be derived for nonlinear processes.
Predictive control is the only methodology that can handle process constraints in a systematic way during the design of the control strategy. Predictive control is an open methodology. That is, within the framework of predictive control there are many ways to design a predictive controller. Feed-forward action can be introduced for compensation of measurable disturbances and for tracking reference trajectories.

Unavoidably, predictive controller design has some drawbacks. Since predictive controllers belong to the class of model-based controller design methods, a model of the process must be available. In general, in designing a control system two design stages can be distinguished: modeling and controller design. Predictive control provides only a solution for the controller design. A second drawback is due to the fact that the predictive control concept is an open methodology. This means that different control strategies can be derived and so different behavior of the Hybrid System will be yielded. Therefore, a unified approach to predictive controller design is needed, which allows treatment of each problem within the same framework and results in significant reduction in design costs. Such a unified approach is developed and it unifies the strategies for stand-alone PV Hybrid Systems.

2. THE PREDICTIVE CONTROL CONCEPT [1]

Usually, predictive controllers are used in discrete time. The predictive controllers will operate the hybrid system with two inputs (the energy from the diesel and the battery inverter) and one output (the delivered energy to the loads minus the energy from the PVs). As it is illustrated in Figure 1, the time scales in parts a, b, c, d, e and f are time scales relative to the sample k, which denotes the present. The time scales shown at the bottom of Figure 1 are absolute time scales. Consider first, Figure 1 a, c and e and suppose that the current time is denoted by sample *k* which corresponds to the absolute time *t.* Furthermore, $u_d(k)$, $u_b(k)$ and y(k) denote the diesel unit output for stand alone system, the battery inverter output and the station unit output at sample *k*, respectively. These functions are expressed mathematically as follows:

$U_d=[u_d(k),\ldots u_d(k+H_p)]^T$,$U_b=[u_b(k),\ldots u_b(k+H_p-1)]^T$,
$\hat{y}=[y(k),\ldots,y(k+H_p)]^T$

where: H_p is the prediction horizon and the symbol ^ denotes estimation. Then, a predictive controller calculates such a future controller output sequence u_d and u_b (shown in Figure 1 d and f), where the predicted output of the hybrid system corresponds to the load profile of a small island for a typical day.

Rather than using the controller output sequence determined in the above way, in order to control the process in the next H_p samples, only the first element of this controller output sequence (=$[u_d(k),u_b(k)]$) is used to control the process. At the next sample (hence, at *t+1*), the whole procedure is repeated using the latest measured information. This is called the ***receding horizon*** principle and is illustrated by Figures 1 b, d and f, which show what happens at time *t+1*. Assuming that there are no disturbances and modeling errors, the predicted process output $\hat{y}(k+1)$, predicted at time *t* is exactly equal to process output y (k) measured at t+1.

Now, again, a future controller output sequence is calculated such that the predicted process output is solved under minimization of energy consumption. In general, this controller output sequence is different from the one obtained at the previous sample, as it is illustrated in Figure 1 c and e. The reason for using the receding horizon approach is that this allows us to compensate for future disturbances or modeling errors. For example, due to a disturbance or modeling error the predicted process output $\hat{y}(k+1)$ predicted at time t is not equal to the process output y (k) measured at t+1. Then, it is intuitively clear that at time t+1 it is better to start the predictions from the measured process output rather than from the process output predicted at the previous sample. This way, the predicted process output is now corrected for disturbances and modeling errors. A feedback mechanism is always activated. As a result of the receding horizon approach, the horizon over which the process output is predicted shifts one sample into the future at every sample instant. The process output is predicted by using a model of the process to be controlled. Any model that describes the relationship between the input and the output of the process can be used. Hence, not only transfer-function models can be used, but also step-response models, state-space models and nonlinear models. Further, because the process is subject to disturbances, a disturbance model will be added to the process.

In order to formulate mathematically the way to minimize the fuel consumption, a criterion function is used. The criterion function is a function of $\hat{y}$, u_b, and u_d.

The criterion function is:

$$J=\sum_{i=1}^{H_P}(u_d(k+i))^2=\sum_{i=1}^{H_P}(\hat{y}(k+i)-u_b(k+i))^2$$

where the SOC constraint may be: $40\% < u_{SOC} < 90\%$
where u_{SOC} is the estimated SOC of the battery bank.
and the allowable power variation per time step may be: $0\% < d\,(\mathbf{u_d}, \mathbf{u_b}) < X\%$
the magnitude of X should be defined by a well-experienced operator.
Now the controller output sequence u_{opt} over the prediction horizon is obtained by minimization of J with respect to **u**: $u_{opt}=\arg\min_{u_d} J$

Then, $\mathbf{u}_{opt}$ is optimal with respect to the criterion function that is minimized taking into consideration the deterministic modes of diesel unit and battery bank.
The control strategy, together with the various components developed, is going to be implemented and tested in the pilot plant at CRES, in Greece.

3. THE EXPERIMENTAL PILOT PLANT AT CRES

A pilot plant serving all the options of the Control Strategy is necessary. For realistic simulation and testing purposes CRES has set-up a Hybrid system at its premises with

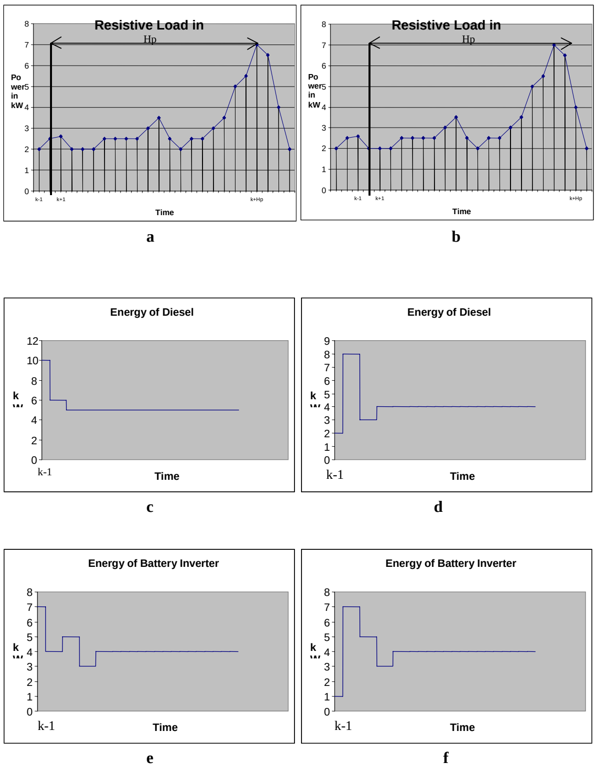

Figure 1: Receding horizon predictive control for the hybrid system. Parts a, c and e denote the situation at k sample, while parts b, d and f denote the situation at k+1 sample.

energy producing and load units connected to an AC grid. All components are connected to a single twisted pair wire bus. The system may be composed of a 4.4 kWp PV array, mounted on one axis sun tracker, a 9 kVA four quadrant battery inverter (96 VDC-220VAC), a 12 kVA Diesel electricity generator, ohmic, capacitive and inductive loads. An operational control unit which communicates with the local control units, controls voltage, frequency and power and operates as a data acquisition unit. The block diagram of the Experimental Pilot Plant layout is shown in Figure 2.

The aim of the experimental application was a standardized applicable system technology which will allow a variety of different hybrid islands supply situations to be covered. Combined with a standard communication bus for operational control, a basis is defined for future development of a set of fully compatible units, which can be integrated into various hybrid systems in islands.[2]

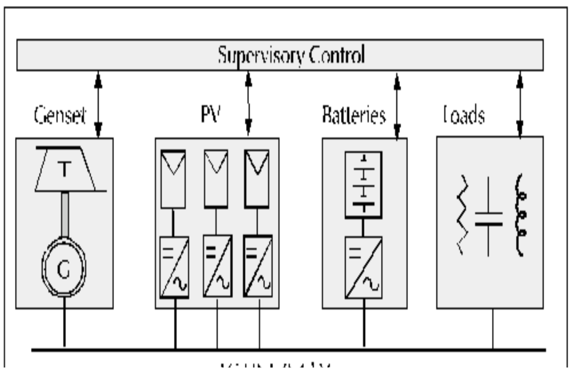

Figure 2: The block diagram of the Experimental Pilot Plant at CRES

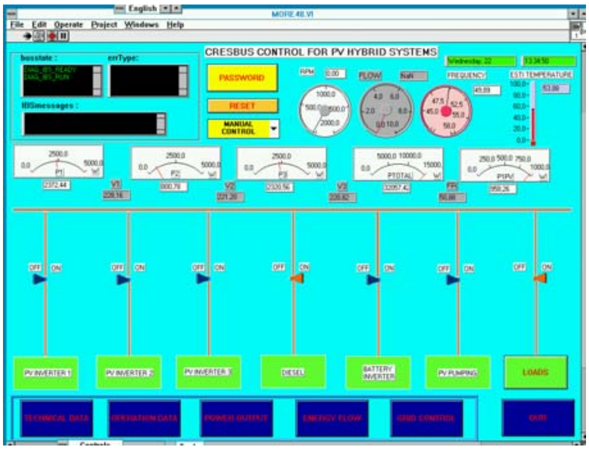

Figure 3: Supervision and Automation Control of Stand-alone PV Hybrid Systems

Interbus-S and EIB have been chosen for the communication between the units of the experimental plant at C.R.E.S. A software prototype has been developed at this stage, based on LabVIEW, as presented in figure 3. The Predictive Control Strategy can be tested on this pilot plant.

Figure 4: Photovoltaic array of 4.4kW$_p$

The Supervising Control has been made by means of the Fieldbus and the user-friendly LabVIEW program. The central supervisory control unit sets the reference state of the power supply system and receives the information about the actual state of each component. The total cost of using EIB is much lower than using a Fieldbus (up to 80% cheaper) with the same reliability and quality. For the moment, the experiments have already been started using EIB modules to control the PV units. Later on, it is planned to use the Sunny Island Battery Inverter from SMA, because it provides the option to communicate through the EIB communication protocol. The communication between EIB modules and LabVIEW was successful via B-Con.
The graphical B-Con editor serves to visualise the bus and management functions. The purpose of all these experiments is to simulate a stand-alone small Greek island as a Hybrid System. Figure 4 presents the photovoltaic array of the PV-Hybrid system and figure 5 depicts the distribution board, which measures and controls the power from photovoltaics. Notice that Interbus-S modules are used to measure the power from photovoltaics, while EIB modules switch on or off the SMA inverters.

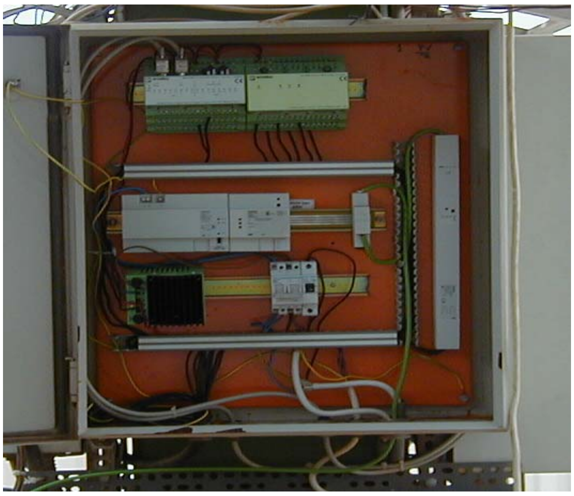

Figure 5: Distribution board of Interbus-S and EIB modules for the photovoltaic array

In the following figures, the experimental results are presented between May 9 and May 18 1999. The figure 6 presents the power flows of the hybrid system over a time period of 9 days. It is noticed, that during the first day the batteries are being charged and the loads have been switched off.

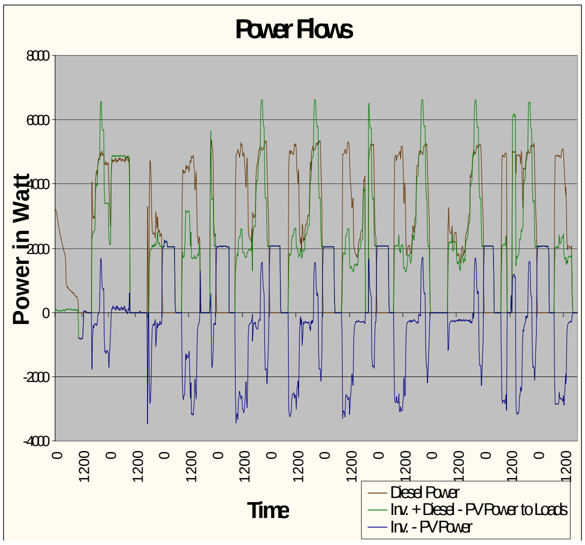

Figure 6: Power Flows

The negative values of power correspond at the times when the batteries are being charged. The PV power is contributing directly on the loads and reduces the load presented to the inverter and diesel generator by the value of its instantaneous power. The maximum instantaneous AC power offered by the two PV inverters together was 1 kW.

Figure 7 presents the battery bank state, in terms of voltage and flow of Ahrs to and from the batteries. The negative flow of Ahrs means that there are being charged and the positive that they are discharged. The voltage became temporarily zero, when the inverter was turned off.

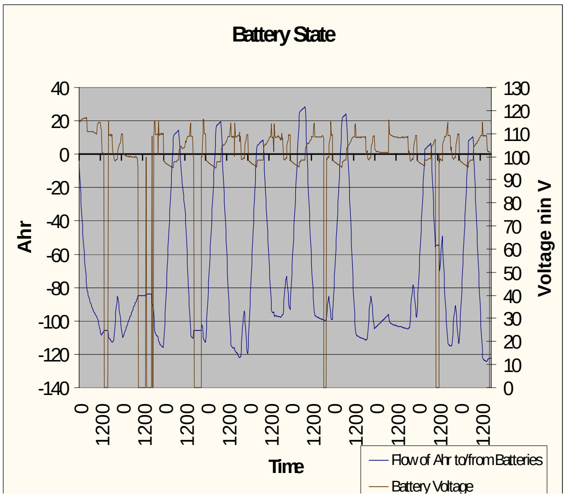

Figure 7: Battery State

By presenting, in the figure 8, the power flows of one day, the picture about the operation of the pilot plant becomes clearer. Notice that the effective load during the daytime morning hours is much higher than the resistive load, due to charging of the batteries.

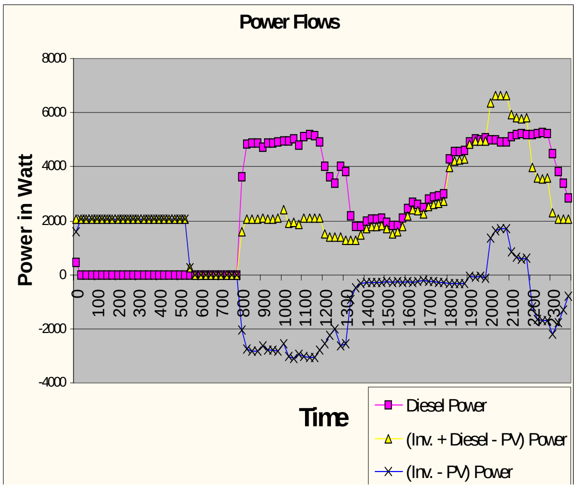

Figure 8: Power Flows

In the last figure 9, the energy produced daily by the diesel generator is presented next to the energy provided to the resistive loads without counting the energy contributed in a day by the photovoltaics, which in any case it is of the order of 5 kWh.

Therefore, during the period of 10 days we had 542.59 kWh of energy produced by the diesel generator, while the energy consumed by the loads, excluding the energy provided by the photovoltaics, was 475.14 kWh. Therefore, the energy efficiency of the system is obtained by a simple division of the two numbers, 475.14/542.59 = 87.5%.

Furthermore, during the same time period the light diesel fuel consumption was monitored. It was noted that, 305 liters of fuel were used for the production of 542.59 kWh of electric energy. Therefore, the energy consumption of the diesel generator was 562 ml/kWh or 469gr/kWh.

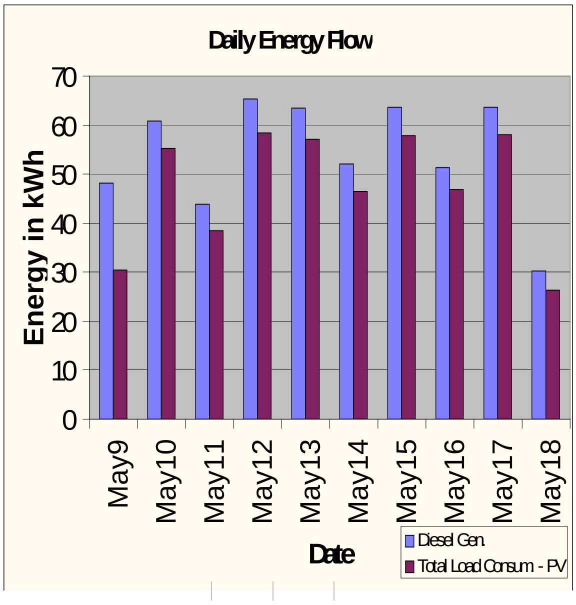

Figure 9: Daily Energy Flow

4. CONCLUSIONS

The Predictive control strategy developed here provides a worthy energy saving for a stand-alone PV Hybrid system. EIB technology seems to be the optimum choice for communication interface between the units of the hybrid system because it can combine the operational control in Hybrid Systems with home automation. The use of E.I.B. technology opens the way for compatibility of products from different manufacturers of PV components and Home Automation, opening the market in both directions.

REFERENCES

[1] Soeterboek R. (1992), “Predictive Control. A Unified Approach”, Prentice Hall International, Englewood Cliffs, N.J.

2] W. Kleincauf, F. Raptis, P. Romanos et.al, “Modular Systems Technology For Decentral Electrification”, 13th European PVSEC, Nice France, October 1995