Predictive Control Strategy for Stand Alone Hybrid Systems using Industrial Fieldbus

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ABSTRACT: The paper focuses on the design and development of a Predictive Control System for stand alone Hybrid Systems using Industrial Fieldbus. A way is indicated to transform island grids powered by diesel generators into hybrid ones with the main power contribution coming from distributed PV and Wind inverters. The daily production and consumption cycles will be balanced with battery storage allowing further the evolution to a 100% renewable energy system. The development of modular components (hardware and software) needed for this purpose is required as well.
Throughout the evolution process of a typical island system, the Grid Master Control System (GMC) goal is to achieve relevant improvements in terms of power availability, frequency and voltage regulation, fuel and maintenance savings, air emission and noise reduction.
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1. PREDICTIVE CONTROL FOR STAND ALONE HYBRID SYSTEMS [1]

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 Wind Turbine, a Photovoltaic generator unit, a battery inverter and a load simulator for a typical small Greek island.

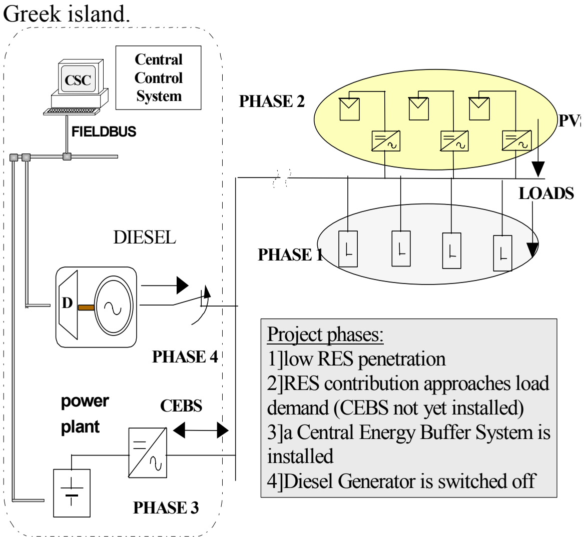

Figure 1: Block diagram of a hybrid system.

A Grid Master Control unit (GMC) is required to manage diesel, energy buffers and PV generators. The Grid Master Control has to solve the following problems:

- frequency and voltage regulation;
- interaction between the centralised energy buffer, the diesel generators and distributed
- Wind Turbines
- photovoltaics generating units;
- daily operating modes policy;
- alarms and emergency management;
- black-start procedure

2. GMC OBJECTIVES[2][3]

The basic idea of the design is not to centralise the control of the distributed PV and Wind inverters in order to reduce costs and to increase system simplicity and reliability. Such a non-conventional solution requires some special control actions that are shortly described in the paper.
The Grid Master Control goal is to achieve the following improvements for the typical island systems:

2.1. Power Quality

- Power availability; the GMC is expected to bring considerable improvements in terms of stability of the local utility grid, reducing faults disturbances due to small isolated systems' intrinsic weakness
- Frequency regulation; to fully satisfy standards' requirements for frequency range in non-interconnected electrical systems, the grid frequency must be kept within rated frequency 2% over 95% of a week, and rated frequency 15% over 100% of a week. The target is to reach better results with a narrow frequency deviation.
- Voltage regulation; according to international standards, the system voltage, in normal operating conditions, must be kept within VR 10%, where VR is the system rated voltage.

2.2 Costs Savings

- Fuel savings; appropriated design of the GMC and its strategies should lead to diesel fuel savings
- Maintenance and machinery life cycles
- the GMC implementation will positively affect the rotating generating units' availability and will reduce the maintenance costs.

2.3 Environmental issues returns

- Air emission reduction;
- Noise reduction

A must of the project is to allow the transformation of existing conventional grids into hybrid grids to be gradual, in order to gain acceptance from local utility companies. Therefore, great importance is given to technical solutions, which guarantee easiness, adaptability and low impact over existing systems.

3. THE PREDICTIVE CONTROL CONCEPT [4]

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 Wind and 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.

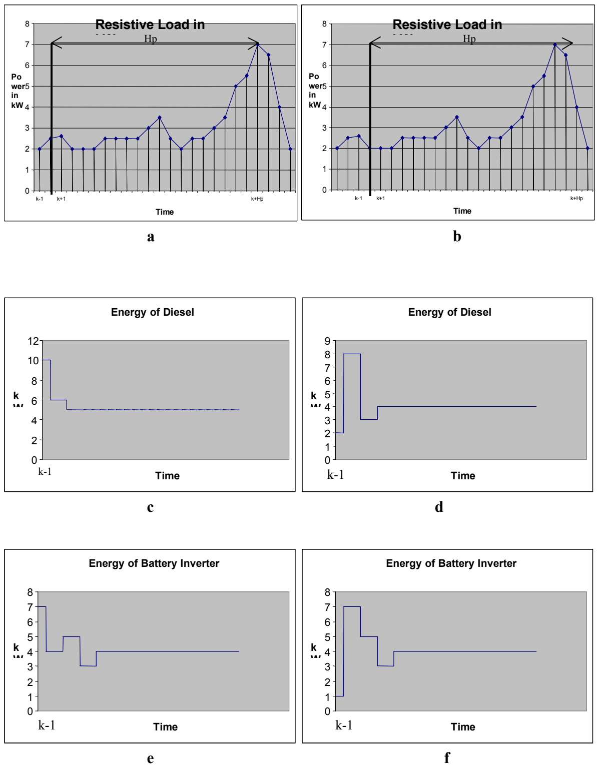

Figure 2: Receding horizon predictive control for the hybrid system. Parts a, c and e denote the situation at k sample, while parts b, d and f denote the situation at k+1 sample.

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.

4. 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 energy producing and load units connected to an AC grid. All components are connected to a single twisted pair wire bus. The system includes of a 4.4 kWp PV array mounted on one axis sun tracker, 3KW PV inverter from TOTAL ENERGIE, a 9 kVA four quadrant battery inverter (CEBS, 96 VDC-220VAC) from ANIT, a 12 kVA Diesel electricity generator, ohmic, capacitive and inductive loads and a wind simulator. An operational control unit which communicates with the local control units, controls voltage, frequency and power and operates as a data acquisition unit.

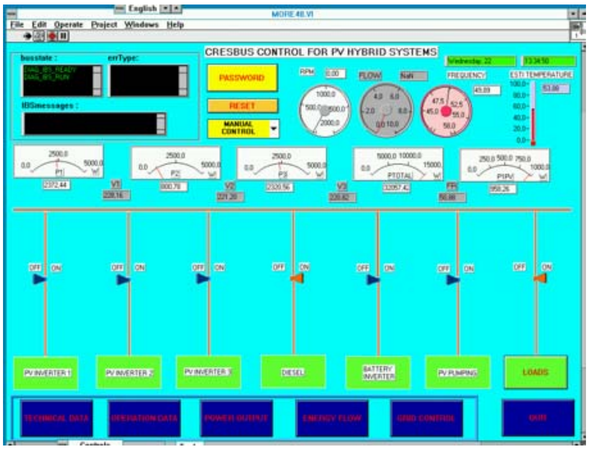

Figure 3: Supervision and Automation Control of Stand-alone Hybrid Systems

Interbus-S 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. Figure 4 depicts the distribution board of Interbus-S modules for the load simulator. The Predictive Control Strategy can be tested on this pilot plant.

Figure 4: Distribution board of Interbus-S modules for the load simulator.

In order to experiment on the energy management of the hybrid system two different strategies are examined. The idea of the first experiment was to inject power from the battery inverter during the period of the peak load demand, therefore reduce the maximum power generated by the diesel generator. The batteries are charged during the period of low load demand, using the same amount of energy that they injected to the grid. The daily load demand profile used to simulate the power consumption of the grid, which is depicted in figure 5, is exactly the same in the two cases. Notice that the first three hours of the day are not shown on the diagrams. The following figures depict the experiments for strategy 1. The figure 6 diagram shows how the cover of load demand is distributed between the diesel genset and the battery inverter, as well as the batteries charging and discharging time periods. The chart 7 shows the diesel fuel flow.

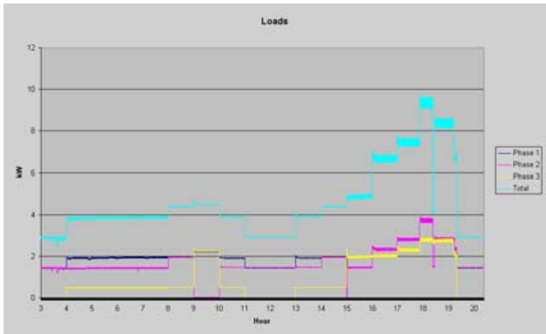

Figure 5: Daily load demand profile.

Strategy 1:

Figure 6: Power flows of the diesel generator, the battery inverter and the load demand.

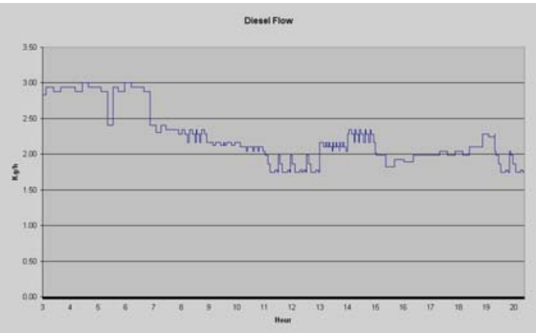

Figure 7: Fuel power flow of the diesel genset (kg/h)

The idea of the second experiment was to use the batteries to cover the whole load demand during a period of base load demand ,while the diesel genset is switched off. Then again we charge the batteries using the same amount of energy that they injected to the grid. The results of the experiments are demonstrated in the following charts in the same order as in strategy 1.

Strategy 2:

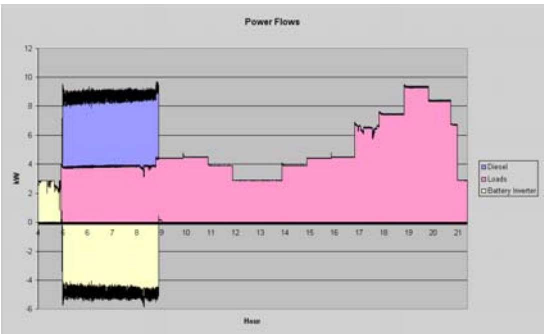

Figure 8: Power flows of the diesel generator , the battery inverter and the load demand.

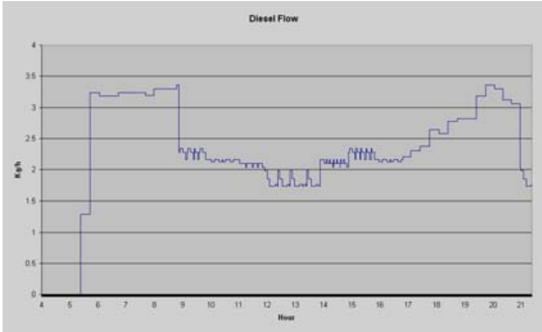

Figure 9: Fuel power flow of the diesel genset (kg/lt)

The total fuel consumption was measured 53.56Kg or 64.16 lt, when strategy 1 was implemented. In the second case, the consumption was 44.21 Kg or 52.96 lt. This means that 17.5% fuel saving can be achieved applying the second strategy. In general, maximum energy saving can be obtained when an accurate load prediction is attained. Notice that the load profile that is used in the experiments includes the energy, which is produced by PV and Wind Inverters.

Notice also that measurements for the frequency of the grid were also taken, yielding high Power Quality. During the experiments the frequency variation range was less than 0.004 per unit.

5. CONCLUSIONS

The Predictive control strategy developed here provides a worthy energy saving, for a stand-alone Hybrid system. At the examined case, up to 20% fuel saving can be achieved . Grid Master Control in combination with the Predictive Control Strategy seems to be the optimal solution for the gradual penetration of RES in island grids.

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