Hybrid modeling of renewable energy systems and its application to a hot water solar plant

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Abstract: A family of models that can be applied to various types of renewable energy plants is proposed. The methodology is used to model a solar plant for the production of sanitary water (the hot water production system installed at the "Hospital Universitario Virgen del Rocío", Seville, Spain). A detailed examination of the behavior of the plant has produced a model which has served to identify niches of inefficiency in the operation. The model is later used to tune the parameters of a controller to improve operation.

Keywords: renewable energy, hybrid, random, model based control

1. INTRODUCTION

The search for alternatives to traditional energy sources is an important issue because of the need to reduce pollution. Renewable energies are difficult to use because of, among other factors, the uncertainty about the availability of primary resource. To address this problem the study of hybrid systems can be considered, using various primary sources and energy storage systems (Zambrano 2008, Zambrano 2006).

A typical hybrid renewable energy system contains two or more sources of renewable energy (solar thermal, solar photovoltaic, wind, biomass, hydro, etc..) that are integrated to provide electricity or heat, or both. The installation consists of several interconnected systems to meet common goals. Each of these subsystems has its own dynamics and characteristics. In this paper we propose a model structure, compatible with renewable energy systems, composed of various sub-systems and relations between them.

The subsystems can be connected in different ways to operate in different modes. These changes in the topology are given by switching signals. Most existing work in literature to handle switching systems use linear or piece-affine. The nonlinear nature of the various systems and modes of operation and the operating restrictions (security, economics, etc.) that all the industrial processes present have been poorly treated. These problems, added to the effect of uncertainties in modeling and the availability of energy resources make the optimization of the operation of the system with uncertainties a significant challenge for research. The fundamental objective that arises is developing control strategies is to optimize renewable energy hybrid systems.

In this work a generic approach for modeling renewable energy systems is presented, and it will be applied to a solar plant. For this example application the modeling work will be performed by modeling each of the parts of the system, getting a global model and simulating it to validate the model with experimental data.

2. GENERIC RENEWABLE ENERGY MODELS

A tetrahedral structure is proposed for renewable energy systems, to be called " RESCUE " by the English acronym of its component elements. This tetrahedral structure is composed of the following sub-systems:

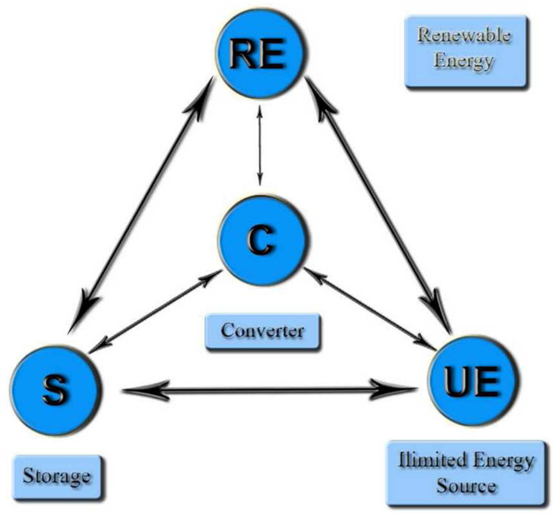

Fig. 1. RESCUE Structure

- "RE": Renewable energy. Renewable energy source that fuels consumption
- "S": Storage. Energy storage subsystem.
- "C": Converter. It conveys the available energy to the final element.

- “UE". Unlimited Energy. Non-renewable auxiliary energy source that provides energy if the demand can not be satisfied by the other subsystems.

The relations between the subsystems are energy transfers. This type of structure proposed, besides having a physical sense, is useful for control. Control strategies on a generic system can be easily particularized to various renewable energy systems. The power of the proposed structure is its applicability to many different problems, capturing the idiosyncrasies of each particular one.

3. APPLICATION: BRIEF PHYSICAL DESCRIPTION OF THE PLANT

The hot water production system installed at the "Hospital Universitario Virgen del Rocío" includes the collectors installed on the covers of Women's Hospital, the cells on the outside near the northern wing of the sub-basement of the building, and the engine room of the hospital basement and it attends the demand of Women's Hospital and Children's Hospital.

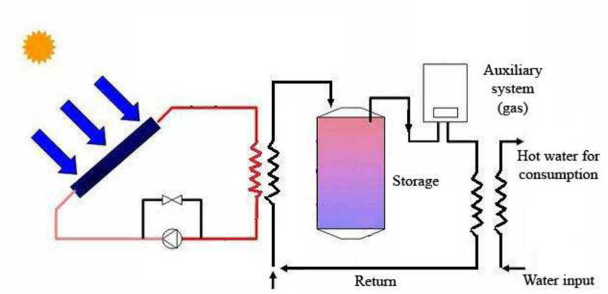

Fig. 2. Global scheme of the plant

The general outline of the plant consists of two separate circuits, the so-called "primary circuit or charging circuit" and the so-called "secondary or discharge circuit". There is a distributed solar collector field on the campus, which has 330,000 square meters construction.

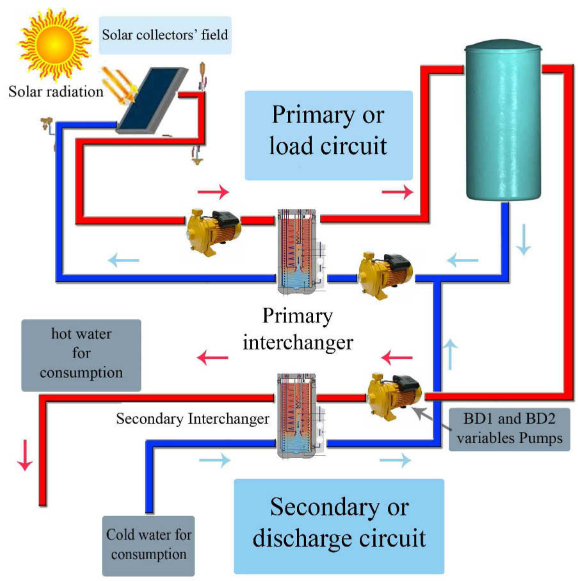

Fig. 3. General scheme

This facility meets the hot water production scheme with exchange between the primary circuit and the solar accumulation and between the solar batteries and the auxiliary discharge accumulators or consumption. Thus, the facility has, therefore, of the following subsystems:

- Primary circuit of solar collectors with heat exchanger
- Secondary solar circuit or load circuit and solar tank
- Discharge circuit
- Solar exchanger for discharge or consumption
- Hot water consumption circuit

The structure of this plant perfectly fits the “ RESCUE " model type proposed and described above. The energy interchange between the subsystems is done through water flows that carry thermal energy in order to bring the output temperature as much as possible to the required value ($60°C$).

The “RESCUE" model of the Women Hospital's solar plant results as follows:

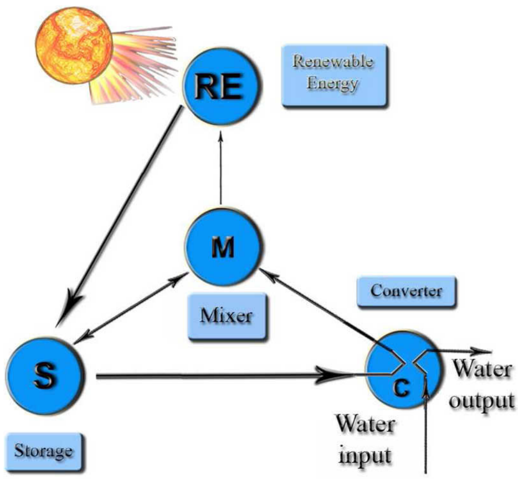

Fig. 4. Specific RESCUE model for the Women Hospital's solar plant

This scheme does not cover the entire system, but only the part under study. The nonrenewable energy source is not taken into account, but it is been included as an external input.

4. GLOBAL MODELING

The objective consists on building a plant model (M.R. Arahal 2006, Berenguel 1997) from experimental data, which conforms sufficiently to the observed facts. This will take several data series considered sufficiently representative. Values of all inputs, outputs, internal variables and disturbances are measured.

In the real plant, there are two storage tanks that are modeled as such, taking into account the stratification in them. There are also heat exchangers, which are modeled by grouping (treating the whole exchanger as if they were only one). In the next subsections the theoretical models used for modeling are detailed.

4.1 Tanks

In a water tank the water is at a higher temperature at the top of the deposits and at lower temperature at the bottom. This fact creates a zone of warm water in the middle section, that should be reduced in order to prevent an environment conducive to the proliferation of bacteria such as Legionella. In health care type facilities is vital to minimize the middle zone. In any case, it will always exist a certain volume of accumulation not to be used having a temperature lower than the minimum for use.

The energy balance (Blandin 2007) on the storage tank is used to model the temperature.

It is possible to write the energy storage capacity of tanks for

$\Delta T = T_{dep} - T_{F2}$

as:

$Q_{dep} = (m \cdot C_p)_{dep} \cdot (T_{dep} - T_{F2}) = C_{dep} \cdot (T_{dep} - T_{F2})$

being Q_{dep} the heat added to the fluid between the temperatures T_{dep} and T_{F2}, m is the mass flow of fluid in kg/sec and C_{dep} its heat capacity. The development that follow is then performed for a case without stratification (with a single layer).

Making an energy balance for a tank with a single layer, the internal energy change of the system must equal the sum of the heats and charges brought into play:

$$C_{dep} \cdot \frac{dT_{dep}}{dt} = Q_{col} - P - UA_{dep} \cdot (T_{dep} - T_a).$$

Where P is the load out of the tank, a function of time, and $Q_(col)$ is the energy collected in the collector, which depends on the type of collector, in the form:

$$Q_{col} = F \cdot C_{col} \cdot (T_{C2} - T_{dep}).$$

Where $C_(col)$ is the heat capacity of fluid flowing through the collector and $T_(C2)$ is the temperature of hot fluid at the exit. Assuming that the pipe connecting the collector with the storage tank is well thermally insulated, one can neglect the fall of fluid temperature along it. With this interpretation, the following expression can be assumed:

$$Q_{col} = CF_{col} \cdot (T_{C2} - T_{dep}).$$

A control function C_F is used, with value equal to 1 when the pump is running and 0 in other circumstances. For a given load, there can be relationships that constitute a system of equations, so that Q_{dep} is determined by the collector performance equation and P by the demands of the load. These equations can be solved to obtain both temperature T_{dep} and the energy changes as a function of time. Auxiliary power can also be included by adding it to the tank or to the flow leaving the tank.

If we now consider a deposit of two layers as in the figure, an energy balance for the upper layer at steady state can be done:

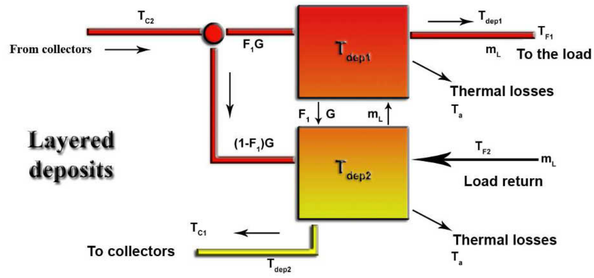

Fig. 5. Tank stratification

$$(m \cdot C_p)_{dep1} \cdot \frac{dT_{dep}}{dt} =$$

$F_1 \cdot C_{col} \cdot (T_{C2} - T_{dep1}) + C_L \cdot (T_{dep2} - T_{dep1}) - UA_{dep1} \cdot (T_{dep1} - T_a)$.

The first term is the gain of the collector, multiplied by a control function F_1 such that:

- $F_1 = 1$ when T_{C2} is greater than T_{dep1}.
- $F_1 = 0$ when T_{dep1} is lower than T_{C2} and T_{C2} is greater than T_{dep2}.

The second term represents the load supplied by the upper reservoir, the return of the charge for this storage system is always made to the section below.

The load delivered by the upper section, is:

$$(m \cdot C_p)_L \cdot (T_{dep1} - T_{dep2}) = C_L \cdot (T_{dep1} - T_{dep2})$$

and the load delivered by the lower section, is:

$$(m \cdot C_p)_L \cdot (T_{dep2} - T_{L,ret}) = C_L \cdot (T_{dep2} - T_{L,ret})$$

where:

$$T_{L,ret} = \text{Temperatura de retorno de masa}$$
$$m_L = T_{F2}.$$

The total load is:

$$(m \cdot C_p)_L \cdot (T_{dep1} - T_{L,ret}) = C_L \cdot (T_{dep1} - T_{L,ret})$$
$$= C_L \cdot (T_{dep1} - T_{F2}).$$

The term $(AU)_{dep1} \cdot (T_{dep1} - T_a)$ corresponds to the losses from the upper section to the external environment. The energy balance for the second section is:

$$(m \cdot C_p)_{dep1} \cdot \frac{dT_{dep2}}{dt} = F_1 \cdot C_{col} \cdot (T_{dep1} - T_{dep2})$$
$$+(1 - F_1) \cdot C_{col} \cdot (T_{C2} - T_{dep2}) + C_L \cdot (T_{F2} - T_{dep2})$$
$$-(UA)_{dep2} \cdot (T_{dep2} - T_a)$$

This can be generalized to a storage of N sections, if two control functions are defined, one for the collector side and another one for the load side.

For the collector:

- $F_i = 1; T_{i-1} > T_{C2} > T_i$

- $F_i = 0$, in other case.

A

$$(m \cdot C_p)_i \cdot \frac{dT_i}{dt} = C_i \cdot \frac{dT_i}{dt} =$$
$$C_{col} \cdot F_i \cdot (T_{C2} - T_i) + (T_{i-1} - T_i) + \sum F_j \cdot C$$
$$+C_L \cdot F_i \cdot (T_{F2} - T_i) + (T_{i+1} - T_i) + \sum F_j \cdot L$$
$$+(UA)_i \cdot (T_a - T_i)$$

4.2 Heat exchangers

The method called effectiveness-NTU (Incropera 2000) is used to calculate the rate of heat transfer in heat exchangers, particularly when there is insufficient information to calculate the logarithmic temperature average.

To define the effectiveness of a heat exchanger it is necessary to find the maximum possible heat transfer that can be hypothetically produced in a heat exchanger through the flow of an infinite fluid. In this case there would exist a maximum temperature difference which is the difference of $(T\_T_(hi)(ci))$ (the temperature difference between the input temperature of hot water flow and the input temperature of cold water flow).

The calculation method is based on the rate of thermal capacity (ie water flow multiplied by the specific heat) $C_(h)$ and $C_(c)$ for the hot and cold water, respectively, and indicates the minor of them as $C_(min)$. This theoretical maximum heat is calculated as

$$q_{max} = C_{min} \cdot (T_{hi} - T_{ci})$$

The efficiency ($varepsilon$) is the ratio between the actual rate of heat transfer and the maximum theoretical rate of heat transfer

$$\varepsilon = \frac{q}{q_{max}}$$

where

$$q = C_h \cdot (T_{hi} - T_{ho}) = C_c \cdot (T_{co} - T_{ci})$$
$$q_{max} = C_{min} \cdot (T_{hi} - T_{ci})$$

The efficiency is a dimensionless quantity between 0 and 1. Therefore, for a given heat exchanger, having the conditions of the input flows the amount of heat that is transferred between the fluids can be calculated:

$$q = \varepsilon \cdot C_{min} \cdot (T_{hi} - T_{ci})$$

For any heat exchanger it can be shown that

$$\varepsilon = f(NTU, \frac{C_{min}}{C_{max}})$$

ε can be calculated using the correlations in terms of the relationship

$$R = \frac{C_{min}}{C_{max}}$$

and the number of transfer units, NTU

$$NTU = \frac{U \cdot A}{C_{cmin}}$$

where U is the heat transfer coefficient and A is the heat transfer area. $U\ cdotA$ is a parameter that is adjusted from an iterative process of identification which seeks to minimize the error.

In this case, the approximation of effectiveness in the case of existing cross-flow heat exchangers in the tables ESDU has been used:tablas ESDU:

$$\varepsilon = 1 - exp(-\frac{1 - exp(-NTU \cdot R)}{R})$$

4.3 Partial modeling

The aim of the model is being a simplification of the plant that serves the specific controller design.

In the actual application work, all process variables are measured. We are interested in building a model that relates the output with the temperature in the tank.

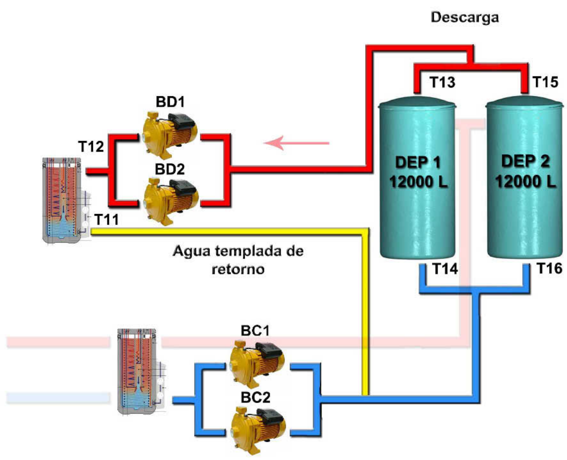

Fig. 6. Partial scheme

With this model, it is not necessary to consider radiation, the collector field or the primary exchangers, since these quantities will influence only the tank temperature, which is taken as a measured input.

The flows of hot and cold water will be used as inputs and cold and hot water temperatures, as outputs. The heat interchange is modeled through physical principles.

5. RESULTS

Real data sets different than those used in identification have been used to validate this model. It aims to compare the actual outputs by those obtained by simulation.

The figure shows the real and simulated outlet temperature. As can be seen, the reproduces quite well the real data.

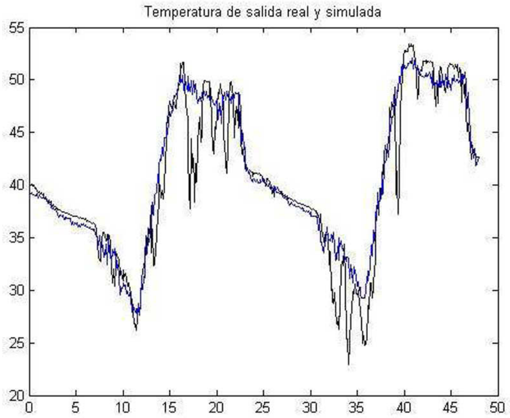

Fig. 7. Results validation

It is considered that the response obtained by simulation is sufficiently similar to real working application, since it essentially captures the dynamics of the plant and the maximum drift from reality is acceptable.

6. CONCLUSIONS

Modeling is a simplification of reality used to be able to work with it and to design specific controllers. The model is obtained through identification from plant data.

The identification procedure includes proposing a simple enough model structure with a behavior sufficiently close to the desired one. After setting the model it is compared with the reality (validation).

Using the model, one possible approach is just tuning properly a simple controller (which provides improved efficiency). Some more advanced techniques could also be proposed: robust control (for disturbance rejection),feed forward control (if there are changes in the operating point) ... In short, the modeling effort is done to obtain controllers that improve efficiency.

For renewable energy systems, a model compatible with many of them is proposed. It has tetrahedral structure and is called "RESCUE" by the English acronym of the elements that compose it. This tetrahedral structure approach is an original idea in this work that arises from research done in this field.

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