# AC 2007-2669: A DECISION SUPPORT SOFTWARE APPLICATION FOR THE DESIGN OF HYBRID SOLAR-WIND POWER SYSTEMS ? AS A TEACHING AID

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# A Decision Support Software Application for the Design of Hybrid Solar-Wind Power System – As a Teaching-Aid


## Abstract

The limited reserves of fossil fuels and the growing global environmental concerns over their use for the generation of electric power have increased the interest in the utilization of renewable energy. This also raises the needs for engineering and sciences programs to provide training in the areas of renewable energy technology. New programs, courses and support laboratories need to be developed and implemented. This paper describes the development of a design module that forms part of a project-based course in solar-wind energy systems taught at one of the author's former institution during the Winter 2006 term. Course materials were developed during the summer 2005 and fall 2006. This module, which is part of the course-support laboratory, consists of a decision support software application used in the design of hybrid power systems, operating in stand-alone or grid-connected modes. This is used as tool in this project-based course. Hourly average wind speed and solar radiation data from the site for the generating unit and the anticipated load data were used to predict performances of the generating system. The support system consists of hybrid (wind, PV/solar, fuel cells, batteries, and diesel-engine generator) power generating systems for utilization as stand-alone or grid connected systems. The performance evaluation is later used in estimating the component sizes needed for generating systems to supply loads reliable. The decision support was implemented using MATLAB/Simulink and IDL software packages. Simple numerical algorithms and models were developed for the size of generation units and for various system components. A simple numerical algorithm was also developed for generation unit sizing. It was used to determine the optimum generation capacity and storage needed foe a stand-alone or grid-connected, wind, PV, and hybrid wind/PV system. The basic objective of this design support module is to complement the classroom teaching of theory concepts through the use of simulation software and to help students in their term design project. Although the program is designed primarily for educational purpose, it can be used to solve practical design problems.


## 1. Introduction.

The interest in renewable energy resources has been growing for several years due to their pollution free availability all over the world and the scarcity of oil and coal resources. The exploitation of renewable resources is also increasingly in demand by the public in order to expand the durability of fossil energy reserves and resources and to decrease harmful energy-related gas emissions. These facts make energy resources attractive for many applications. Of the many alternatives, the "Hybrid Power Systems", where two or more power generation devices are combined to create a synergy with attributes that exceed the sum of the individual components has been considered a promising option toward meeting the continually increasing energy demands and the environmental concerns. "Hybrid Power Systems" are power generation systems in which a heat engine such as gas turbine or diesel engine is combined with one or more non-heat-engines, such as fuel cells, wind generation systems or photovoltaic systems.

The working definition of "Hybrid Power Systems (HPS)" is evolving, but currently the following statement captures the basic elements[1-4, 6-9, 10, and 13-16]:

- Hybrid power systems combine two or more energy conversion devices that, when integrated provide: (1) additional advantages over those devices operating individually, and (2) a synergism that yields performance which exceeds the sum of its components.

Hybrid configurations are likely to represent a major percentage of the next generation's advanced power systems.

The industry now requires engineers and technicians trained in these emerging areas of renewable energy who can compete in an environment characterized by reduced development times, lower development budgets, and increased expectations of high quality. These demands are presented within a new framework of intense global competition and the shortages of qualified engineers. These facts support the necessity to design and develop new courses, laboratories, experiments and programs, and to update, improve or change the content of the existing ones in the areas of energy conversion and renewable energy. The modernization of laboratories and associated courses has been based on the following goals: *creating a motivating environment for the practice of basic concepts and principles*; allowing experimental verification of fundamental laws and concepts, including; providing opportunities for immediate correlation between theoretical and experimental results leading to the repetition of the procedures if necessary; and *stimulating team work and interaction throughout the laboratory session*, from experiments to design to the elaboration of technical reports.

Power systems, electric machines, renewable energy sources, direct energy conversion, control, instrumentation and power electronics are key topics in the modern study of renewable energy conversion systems[7, 8, and 11]. Any new laboratory should address these areas and it must do so in a safe and attractive way. Students need access to computers, databases and necessary instrumentation. Perhaps the most important requirements of a renewable energy conversion laboratory are the following: a) comprehensive in scope but uncompromising in meeting educational needs; b) practical in emphasis and relevant to industry; c) attractive to students and able to enhance their experiences in energy conversion; and d) flexible and modular in structure.

## 2. System Configurations and Optimization

A single energy source system, e.g., a standalone solar energy system, or wind generator cannot provide a continuous source of energy due to low availability during the no-sun period or lack of adequate wind. This implies that in order to achieve the high-energy availability required in some applications such as: lighting, electrification of remote areas and telecommunication, it is necessary to oversize the rating of the generating system (e.g. surface of the photovoltaic array, rating the wind turbine). In the past, hybrid systems have been preferred to remote systems like radio telecommunication, satellite earth stations, or at a site that is far away from a conventional power system [3, 4, 7, and 11].

Today there is a trend to update the existing one-source systems (PV, Wind, hydro) into hybrid systems[4.5, 10]. Hybrid wind/photovoltaic (PV)/diesel power generation systems have been studied extensively in the last three decades. Energy storage is needed in these systems due to the intermittent nature of wind and solar energy. Hourly average wind speed and solar insulation data over a 4-year period was collected from several weather stations across the United States mid-west areas. Average hourly load demand for a typical home in Mid-west and Canada was obtained from studies such as presented in references [1-3].

**2.1 Problem formulation.**

In designing a HPS, there are several goals, including, among others: security of energy supply, overall efficiency, selection of cheapest and reliable energy generation solution, etc [10, 12-16]. To achieve these goals it is important to highlight all factors influencing the main goal, whether technical/engineering, economical, political or social. Thus, a hierarchical structure of the system is built descending from the main goal down to the constraints and finally to the outcomes, which represent the design objectives (attributes). The various divergences of opinions and influencing factors are identified, weighed, and the objectives are considered accordingly. These are the minimization of both cost and the maximization of system reliability and efficiency. Note that these factors may have in general different weights in the design procedures.

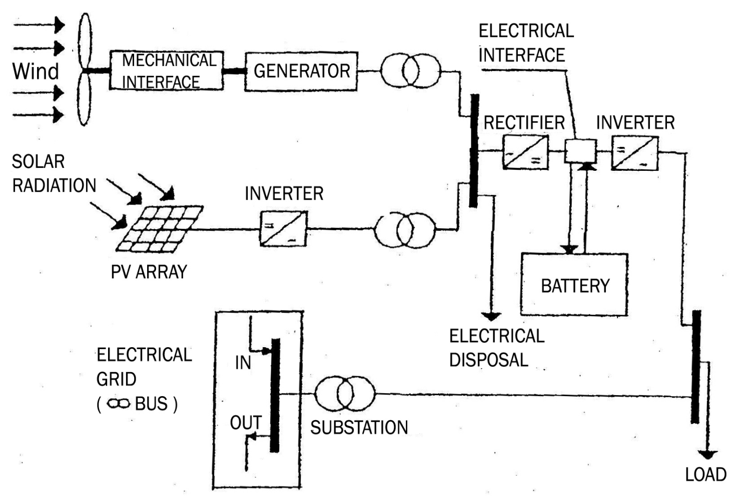


Figure 1: A grid connected hybrid power system.

**2.2 System Modeling.**

After deciding the priority of the design objectives there is a need to know how system components are simulated and what will be the operating strategy of the proposed design. In this project we will analyze and design four different HPS configurations:

1. **HPS 1** – Wind Turbine Generator (WTG) – Photo Voltaic (PV) Array – Batteries Configuration (see Figure 1).
2. **HPS 2** – Fuel Cells – Micro-turbine Configuration
3. **HPS 3** – Fuel Cells – WTG - Diesel Engine Configurations.
4. **HPS 4** – Fuel Cells – Gas Turbine Configurations.

If the wind turbine generator and/or PV array will be included in an HPS than the wind time series and solar insulation data for that site will be required. The user also would require to specify if the HPS would be connected or not with the power grid. Figure 2 shows the configuration of the hybrid power system HPS1 with the grid connection option.

**2.3 System Components.**

**a) Wind Turbine Generator (WTG):** The following model is used to calculate the output power, PW (kW/m$^2$) generate by a WTG:

$$PW = \begin{cases} PW = 0 \quad for \quad V < V_{ci} \\ PW = a \cdot V^3 = b \cdot \Pr \quad for \quad V_{ci} < V < V_r \\ PW = \Pr \quad for \quad V_r < V < V_{co} \\ PW = 0 \quad for \quad V_{co} < V \end{cases} \qquad (3)$$

Where: $a = \Pr/\left(V_r^3 - V_{ci}^3\right)$, $b = V_{ci}^3/\left(V_r^3 - V_{ci}^3\right)$, $Pr$, $V_{ci}$, $V_r$, $V_{co}$ are the rated power, cut-in, rated, and cut-out wind speeds, respectively. The real electric power is calculated as:

$$P_{a,w} = PW \cdot A_w \cdot eff_w \qquad (4)$$

Where: $Aw$ is the total swept area of the WTGs and $eff_w$ is the efficiency of the WTGs and the converters shown in Figure 1.

**b) Photo-Voltaic (PV) Arrays:** The output power, *PS (kW)* a PV array of area '*As*' when subject to irradiance $H$ (kW/m$^2$) is given by

$$PS = H \cdot A_S \cdot eff_s \qquad (5)$$

Where: $eff_s$ is the efficiency of the array and the corresponding converters shown in Figure 1.

**c) Fuel Cells:** A fuel cell generates electricity directly through electrochemical reactions and is more efficient than a heat engine because it eliminates mechanical or rotating parts. Because the performance of a fuel cell is not restricted by Carnot's Law, which limits the heat engine's efficiency, the fuel cells will likely be the core of any high-efficiency hybrid power cycle. The electrical energy conversion efficiency of most fuel cells ranges from 40% to 60% based on the lower heating value of the fuel. Fuel cells operate at high efficiency, regardless of size and load, and the by-product heat from fuel cell reactions can be efficiently used in cogeneration systems, which is another advantage of hybrid power systems. The electrochemical reaction process inside the fuel cell stack is very complicated. In application, we are particularly interested in electrical characteristics of the stack. Export power of fuel cell is:

$$P = E_0 \cdot I + \left( I - \sqrt{I^2 (1 + 4KR) + KI \cdot E_0} \right) / 2K \tag{6}$$

Where: $K$ – the slope of characteristics, represents the power converted by the fuel cell; $R$ is the inner resistance; $E_o$ equivalent potential of fuel cell group (V); and $I$ is the export current density (A/cm$^2$).

**d) Micro-turbines:** Micro-Turbine Generators (MTGs) are small, high-speed, integrated power systems that include a turbine, compressor, generator, and power electronics to produce electric power. MTGs are in sizes of power output 30 to 500 kW [15, 20]. Some package designs are configured for combined heat and electric power cogeneration production. Cogeneration units include additional components, such as hot water heat exchangers, which capture heat from the MTG exhaust to produce useful thermal energy. Micro-turbines offer a number of potential advantages compared with other technologies for hybrid power generation: a) a small number of moving parts; b) compact size and light weight; c) lower energy costs and lower emissions; and d) the opportunities to utilize otherwise waste fuels. Micro-turbines can run on a number of fuels, including: hydrogen, Kerosene, recycled oil, alcohol, or possibly vegetable oil.

**e) Diesel Engine & Diesel Speed Regulator (Governor):** The Diesel engine model gives a description of the fuel consumption rate, which is a function of speed and mechanical power at the output of the engine. A simple first order model usually models the Diesel engine, which relates the fuel consumption to the engine mechanical power. The efficiency of the combustion is the ratio of the effective horsepower developed by the engine and available on its crankshaft to the heat consumed during the same interval of time. A governor can be defined as the mechanical or electro-mechanical device for automatically controlling the speed of an engine by relating the intake of the fuel. Several types of governors exist, such as; mechanical-hydraulic, direct mechanical type, electro-hydraulic, electronic and microprocessor based governors.

**f) Batteries:** Energy from batteries is needed whenever the renewable energy is insufficient to supply the load. On the other hand, energy is stored whenever the supply from the HPS exceeds the load demand. The maximum allowable energy taken or added to the batteries is a percentage of total capacity $C_b$**,** usually taken as 10% of $C_b$ per hour[5]. In addition, to avoid deep discharges the maximum storage level is limited to 20% of what available in the battery before the discharging cycle begin. The behavior of a battery is rather nonlinear and the internal elements are a function of the battery state of charge and electrolyte temperature thus its charge efficiency cannot be considered equal to 1. For this project a rather simple battery circuit was considered (Figure 2). In a later version the authors intend to include a more sophisticate battery models.

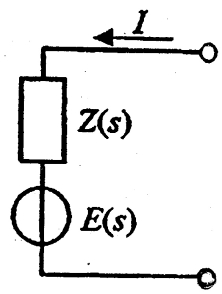


Figure 2: Simple battery electric equivalent circuit.

**g) Electric Grid:** When an electric grid is available than the utilization of renewable energy sources can only be justified on the basis that the reduction in electric utility emissions and/or reducing the dependence of fossil foreign sources are desirable. On the customer side, the use of renewable energy may be attractive if in the future customers have to pay not only for the cost of electric power generation, transmission and distribution, but also for the environmental indirect cost. It is assumed that the energy delivered by the electric grid is always available but limited by the rating of the substation, which establishes the connection with the hybrid power system.

**2.4 Energy Flow**

The following operating strategies are employed:

- The use of electric power generated by HPS components has priority in satisfying electricity demand over that provided by the batteries or by the electric power grid, if available.
- If the total electric power generated by the HPS components is higher than the demand than the additional power will be charged via converters in the batteries.
- After charging the battery the electric power that remains is disposed of.
- If the total electric power generated by HPS is less than the demand than electric power will be discharged from the batteries that supply the demand because once the batteries are bought, their major cost would have been committed and their use is given priority.
- If batteries cannot supply the demand and if the electric grid is available then the electric power is drawn from it.
- If the demand cannot be satisfied then this will result in an electric deficit, which, will be used to compute the expected energy not served (EENS).

Having decided on the operation strategy the next step is to calculate for a proposed design, the cost of generating electricity ($/kWh), the reliability of the design and, finally, evaluate the environmental impact.

### 2.5 Economic Analysis and Reliability Evaluation.

**a) Economic Analysis:** The cost of generating one kWh is calculated by dividing the summation of the present worth of all the salvage values of the equipments, the yearly operation and maintenance costs and the capital investments by the expected yearly energy demand ($E_y$) that is going to be supplied during the life time of the project (N):

$$C = \frac{\sum I_k - S_{pk} + OM_{pk}}{E_y \cdot N} \qquad (7)$$

Where, the summation includes the HPS components, and grid (if included) installations, and batteries. $I_k$ – the initial investment for each component 'k'. $S_{pk}$ – presents the worth of the salvage value of each component '*k*'. $OM_{pk}$ presents the worth of the operation and maintenance costs for each component '.*k*'. Notice that: the design variables of the WTGs, the Fuel Cells, the PV/solar arrays, the micro-turbine, the batteries, the electric grid, etc. are: the total wind area ($m^2$), the size of the batteries (kWh), the fuel cell capacity, the rating of the generators (kW), etc.

**b) Reliability Evaluation:** Reliability is the measure of quality of consumer supply. Any proposed design would have a certain reliability, which is quantified using the expected energy not served (EENS) (kWh/yr). To evaluate the reliability of a HPS, the existence of time series data of load demand (kW), power input, such as wind velocity (m/s), solar irradiance ($kWh/m^2$), fuel cells power output, etc. are necessary.

## 3. Computer-Support Programs

Table 1: Component ratings for an example of stand-alone Wind/PV System

| Component | Rating | Number |
|---|---|---|
| Wind Turbine Generator | 10 kW | 1 |
| Solar Panel | 53 W | 72 |
| Back-up Generator | 3.2 kW | 1 |
| Deep Cycle Battery | 2.1 kWh (Total) | 8 |

The component models presented above were integrated to evaluate performances and characteristics of various hybrid power systems designed to work stand-alone and to generate energy to supply an average house assumed to be located in North America. The hourly average wind and solar power generation are simulated using data collected form weather stations, while the average power demand are taken from references 10, 12, 13, and 14. An example of the component ratings used in simulation is listed in Table 1.

Notice that the rough analysis of the systems discussed in this paper is performed only from the technical point of view. Economic analysis was performed only as a secondary objective of the support-design program, even if it is also a fundamental aspect to be dealt with in order to determine the real value, and hence the viability of a renewable energy system. Figure 3 shows the main screen of the support-design system, while the main types of the power system generators are shown at the bottom of this diagram.

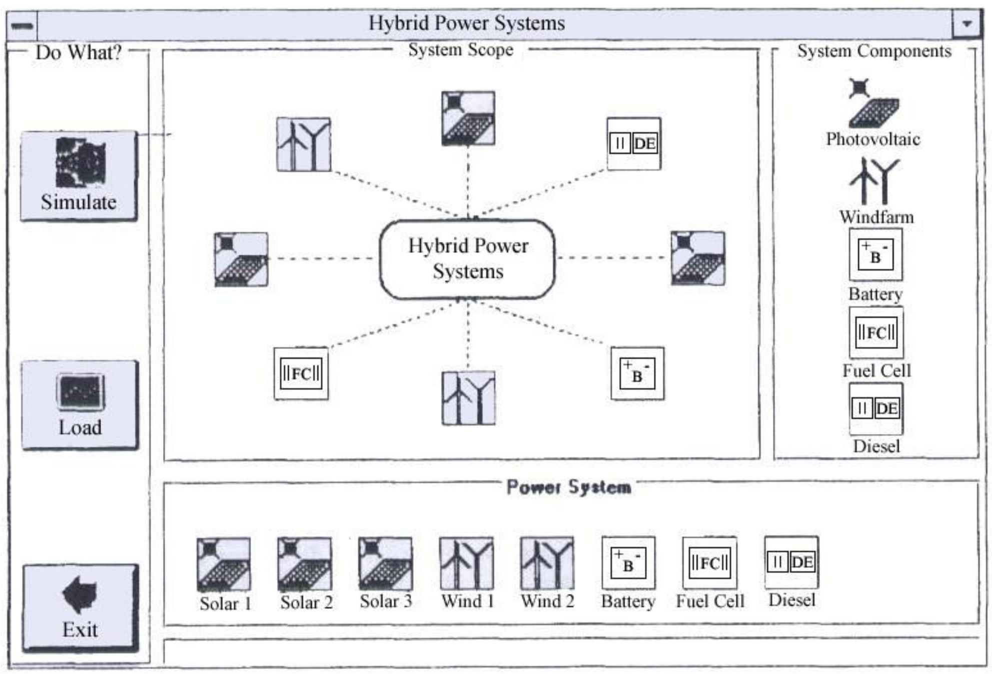


Figure 3: Main screen of the system simulation module giving the structure of a hybrid power system

Figures 4 and 5 show the solar/PV module. Notice that photovoltaic/solar and wind energy systems should be considered in the analysis and design of a hybrid power system as having the greatest long-term potential. Therefore a set of modules was implemented in order to deal with the assessment of classic solar photovoltaic (based on current flat technology) and wind power generators. Although multiple variants can be thought of as far as the design of these kinds of generators there are no significant differences, which are noticeable. Thus, a general-purpose structure for the PV/solar system is proposed as shown in Figure 3, where the most common subsystems are included according to the methodology developed in the previous sections of this paper.

Each subsystem or component can be defined according to given requirements and specifications, such as for the panel and field subsystem in Figure 3, where typical settings and field topology can be updated. A particular feature of this program is the way in which both solar radiation and wind speed is performed. In each case a simulation program based on the average solar radiation and wind time series was designed and coded, and the Markov Transition Matrix (MTM) approach has been implemented in order to generate the synthetic time series[15].

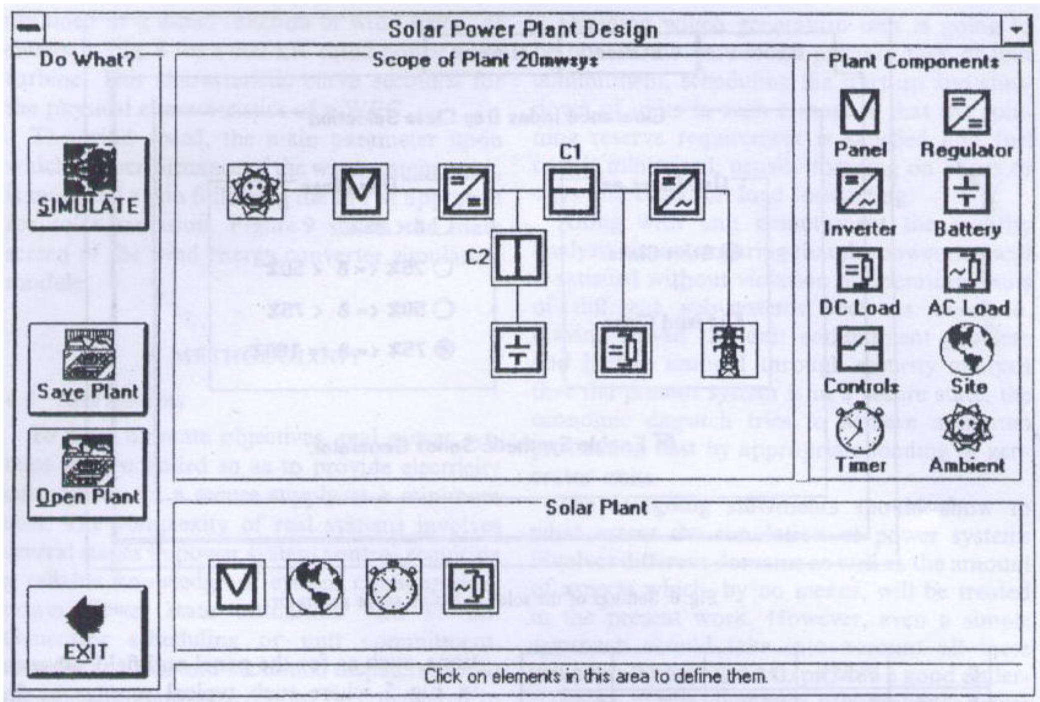


Figure 4: Main screen of the solar/PV power simulation module with the general PV plant structure proposed.

Figure 6 shows the radiation-settings module where stations as well as the start-up transmissivity day-class can be selected, whereas Figure 7 presents a typical wind turbine power output.

A very simple model based on the main characteristic curve of wind turbines has been implemented. Other effects such as turbulence, wind direction, spatial distribution or local factors have not been considered at this stage of the support system implementation remaining to be included in later developments of the support system. Since such a machine is a set of components whose global behavior can be easily represented, the output power of each machine is obtained as a direct function of wind speed, as shown in Figure 4 for a 600-kW rated-power wind turbine. Wind speed, the main parameter upon which the performance of the wind system relies is modeled again following the MTM approach, as mentioned above.

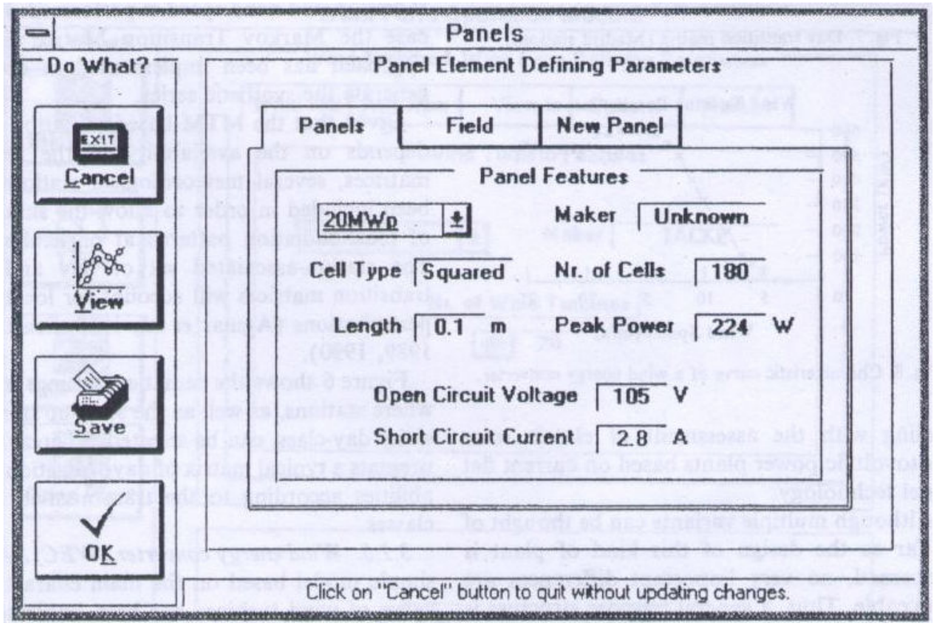


Figure 5: Screen of the panel definition module

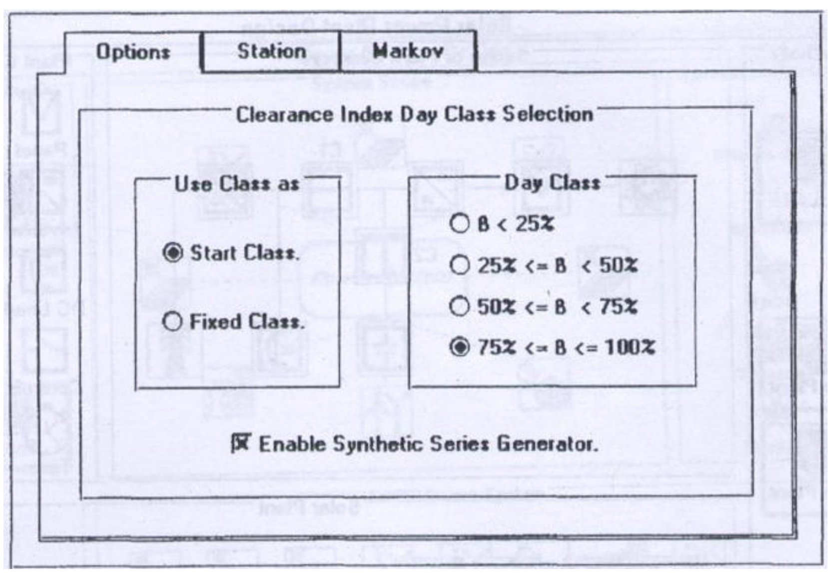


Figure 6: Settings of the solar radiation series generator

Figure 8 shows the main screen of the wind energy conversion simulation module.

### 3.1 Methodology and Program Structure

To meet the ultimate objectives real power systems are controlled so as to provide customers with a secure supply at a minimum cost. The complexity of real systems involves several stages in hybrid power system control requiring a reliable knowledge of system configuration, power flow, and state estimations and so on. Generator scheduling or unit commitment, security analysis and economic dispatch should be the main activities to be considered in different time scales. Deciding which generation unit is going to be put on the bars is the primary task of unit commitment, scheduling the start-up and shut down of units in such manner that the optimum generation is achieved. Along with unit commitment the security analysis aims at ensuring the power demand is satisfied without violation of operating limits of different sun-systems such as an overload. Having solved the unit commitment problem and having ensured through security analysis that the present system is in a secure state, the economic dispatch tries to achieve minimum production cost by appropriate loading of generator units. The demanded power is defined through the appropriate characteristic curves of system components, and once this is defined, the output of wind and solar/PV equipment is computed according to the respective hybrid power system. This intermittent output is then subtracted from the demand of electricity at each simulation, and fuel cell and diesel engine generators are used to complete the difference in energy demands and the loads are so balanced. The result of this allocation process is optimized to lead to a satisfactory load supply. Notice that the load requirements are never met so accurately as to obtain a zero-balance between demand and production. Therefore, an excess of production is to be expected for the sake of reliability requirements. This continuous overproduction is a normal operating state in real systems and the excess of power is supposed to be wasted or dumped appropriately.

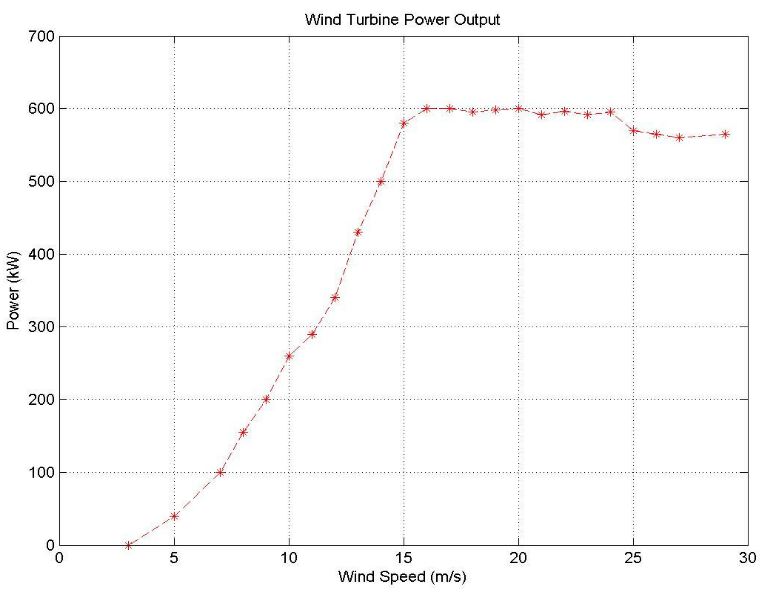


Figure 7: Characteristic curve of a wind energy converter

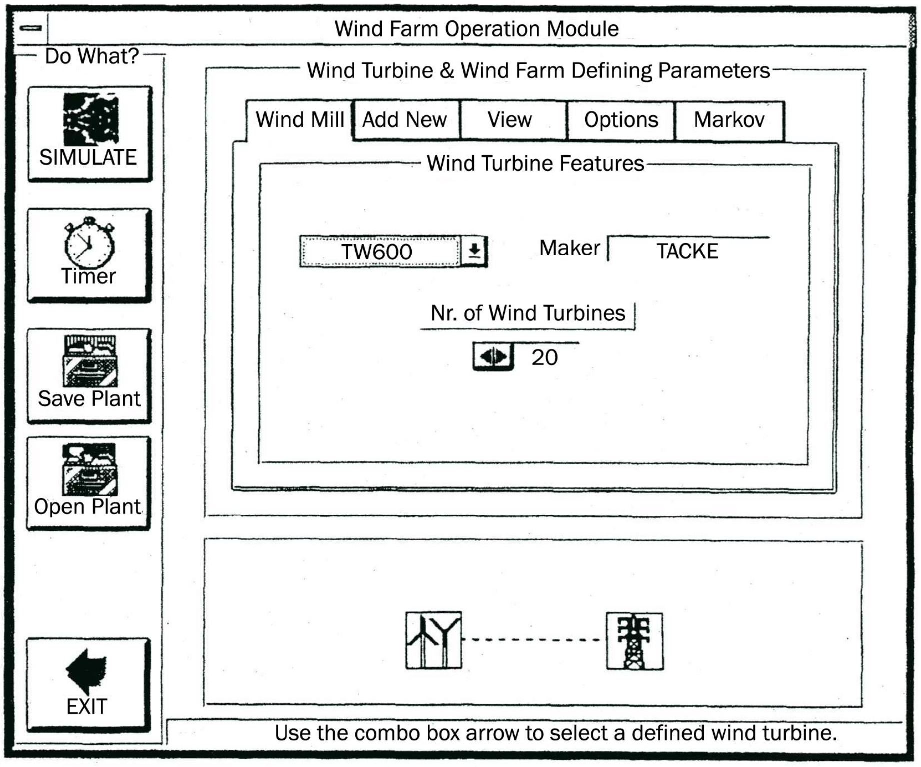


Figure 8: Main screen of the wind simulation module

The support programs were designed and coded using modern standard programming tools for the Windows environment, namely VISUAL BASIC, MATLAB and C/C++, and a user friendly approach implies a rather flexible user-program interface, which clearly defines the two different parts of the system: the interface itself and the program engine. The former is devoted to the communication between the user and the program including auxiliary and database files, and the later mainly devoted to calculation tasks, which have been implemented in the form of a typical Windows dynamic link library (DLL). This contains, at the lowest level, all the defined functions resulting from the modeling of the different hybrid power system components. Solar radiation and wind time series are generated using IDL (Interactive Data language) subroutines, while some power plant subsystems are modeled using the MATLAB software package.

## 4. Discussion, Conclusions and Future Works

A set of computer programs devoted to the simulation of various hybrid power systems has been designed. The purpose of this set of programs is to be used as a teaching-aid in renewable energy courses. The program is designed and developed to be used by the students in order to design and analyze renewable and hybrid power systems. A friendly user interface helps the students select hybrid power system components, the component's characteristics, perform cost and reliability analysis, and to simulate the power output. The support system also integrates these variable-power generators with diesel-engine generators, batteries and fuel cells in the selected hybrid power system configuration. The generation of both solar radiation and wind speed series has been modeled by means of the Markov transition matrix approach. There is also the possibility of testing the effect of different hybrid power system topologies, as well as different irradiance and wind speed levels through typical examples, which should help to properly explain these kinds of systems. Scenario assessment is then made possible in order to compare the technical potential of available resources with the costumer's energy demand to be met.

Future work may imply the addition of new HPS configurations, new system components, and new loads, as well as new wind and solar generation procedures. New functions may be also added the system library and the design of a new user interface and the addition of more powerful graphic facilities.

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