An efficient program for modeling, control and optimization of hybrid renewable-conventional energy systems

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Abstract--In this paper, a generic and an efficient model for hybrid renewable-conventional electrical energy systems is presented. This simulation model is successfully validated by means of HOMER. Moreover, two control strategies for electrical power dispatch are described. Furthermore, an optimization problem is formulated and solved, using Genetic algorithm technique, for optimizing the size of system components where the overall cost of the system is minimized. Four case studies are investigated. The results show a dependence of the size of the system components on the meteorological characteristics of the area under consideration, which validate the proposed methodology.

Index Terms**-- Hybrid energy systems, optimization problem, renewable sources, simulation modeling,**

I. INTRODUCTION

HYBRID renewable-conventional electrical energy systems have been attracted a considerable attention from electric utilities and scientific community in the world. These hybrid systems are widely used to provide electricity to rural or remote areas where the electrical grid is not available. This type of plants is called ‘stand-alone’ power plants. In order to achieve the optimal performance of these hybrid energy systems, they need to be properly designed [1,2]. Therefore, in this paper, we aim at designing the hybrid energy systems in such a way to enhance the system reliability, robustness and efficiency while minimizing the total cost.

During this research work, a simulation model of the hybrid renewable-conventional energy system has been developed. The hybrid system considers all components of the hybrid solar/wind/diesel power plant. The simulation model is presented in section 2.

Moreover, we aim at controlling the considered hybrid system using different control strategies. In fact, two different control strategies are implemented, i.e. a *load following strategy* and a *cycle charge strategy*. Furthermore, an optimization problem is solved in order to optimize the current hybrid energy system. The optimization procedure utilizes the *Genetic Algorithm* to optimize the size of each element and to minimize the total cost. In addition, the proposed procedure is able to select the best control strategy as well as to optimize the tilt angle of the solar panels. The optimization problem is formulated and introduced in section 3.

As real applications, four different case studies are tested. The results of these case studies are given and discussed in section 4. Finally, the conclusions are drawn in section 5.

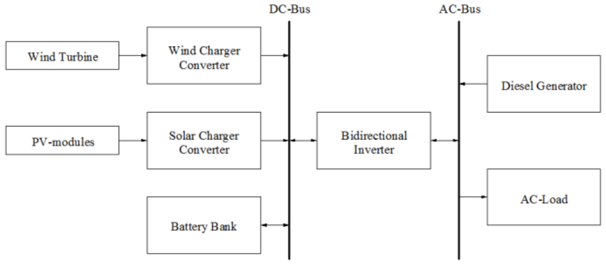

Fig. 1. Schematic diagram of the considered hybrid energy system.

II. SIMULATION MODEL

The considered hybrid electrical energy system consists of a combination between a renewable energy system (photovoltaic solar panels, wind turbines) and a conventional system (a diesel generator) as well as a battery bank. Power converters, e.g. set of inverter/rectifier units, are also modeled. The schematic diagram of the considered hybrid energy system is shown in figure 1.

In order to simplify and generalize the model, the following assumptions are made [3]:

1. The system is considered in a steady-state regime within every time step.
2. The steady-state power, efficiency and energy is considered, no other values are used for the system description.
3. The model incorporates conservation laws, e.g. conservation of the power flow.
4. Equipment breakdowns or planned maintenance are not considered.
5. Costs are additive, and there are no perceptional changes in the plant capacity, unit cost of energy sources and the configuration of the system during the simulation.
6. A time step of one hour is used.

7. The renewable sources, as well as the electrical loads, are constant within each time step.

The developed mathematical model can be divided into several parts; each part is devoted to a certain component.

A. Modeling of solar energy Template

The hourly solar radiation is calculated by checking the hourly relative position of the sun to the earth. Then, an hourly clearness index is generated according to a predefined probability function which depends on the monthly mean clearness index.

These calculations allow to generate the diffuse, beam and reflection part of the solar radiation which can be used in the the HDKR (Hay-Davies-Klucher-Reindl) model to generate the total hourly solar radiation on a tilted surface [4]. This advanced anisotropic model takes into account the circumsolar diffuse and horizon brightening components on a tilted surface.

The model for the solar panel, i.e. Photovoltaic (PV) panels, is made according to [5]. The PV power produced is estimated by the following equation:

$$P_{pv} = P_1 \frac{G}{G_{ref}}.(1+\mu_p.(T_c - T_{ref})).P_{pv,r} \qquad (1)$$

with P_1 being the coefficient depending on cleanliness of the PV-cells, Joule effect and instability of the system characteristics, while μ_P is the temperature coefficient $\left[\frac{1}{°C}\right]$. G is the solar irradiance on a tilted surface and T_c is the working temperature of the PV panels. G_{ref} and T_{ref} are the reference values of the flux radiation and ambient temperature, respectively, i.e. $1000\ Wm^{-2}$ and $25\ °C$. $P_{PV,r}$ is the rated power of PV panel under standard test conditions [5].

B. Modeling of wind energy

Based on the mean monthly wind speed $(\bar{v}_{ref})$, hourly wind speed values (v_h) are generated taking into account a Weibull distribution function:

$$f(v) = \frac{k}{c}(\frac{V_h}{c})^{k-1}\exp[-(\frac{V_h}{c})^k] \qquad (2)$$

with a specific shape factor (k), scale factor (c) and the mean value $(\bar{v}_{ref})$. The hourly wind speed time series have some autocorrelation and daily pattern implemented according to [6].

Further on, the hourly wind speed values need to be transformed into hourly energy values generated from the wind turbines. This can be done by the following formula[7]:

$$P_w = \begin{matrix} 0 & V_h < V_c \\ aV_h{}^3 - bP_{w,r} & V_c \le V_h \le V_r \\ P_{w,t} & V_r \le V_h \le V_f \\ 0 & V_f \le V_h \end{matrix} \qquad (3)$$

Where

$$a = \frac{P_{w,e}}{V_r^3 - V_c^3}, b = \frac{V_c^3}{V_r^3 - V_c^3} \qquad (4)$$

where v_c, v_r, v_r and v_h are cut in, rated, cut out (or furling) and hourly wind speeds, respectively. P_w and $P_{w,r}$ are the hourly output power and the rated output power of the current wind turbine, respectively.

C. Modeling of the diesel generator

The diesel generator is utilized for compensating the power shortage when the power demand is higher than the power produced by renewable energy sources and the battery bank. The model [5] uses the following formula to calculate the fuel consumption:

$$F_{DEG}(t) = F_s.P_{DEG}(t) + F_i.P_{DEG,r}, \forall t \in T \qquad (5)$$

where the fuel consumption F_{DEG} is determined by the *idle fuel consumption* F_i which is the fuel consumption at zero load, and the specific fuel consumption F_s of a particular diesel generator. P_{DEG} and $P_{DEG,r}$ are the output power of the diesel generator and its corresponding rated value, respectively. T is the set of all simulation time steps.

D. Modeling of the battery bank

The battery bank is used as a storage unit to store the energy when the generated power becomes higher than the required load. The battery starts to discharge the stored energy according to a certain control strategy. The state of charge of the battery (SOC) must stay between the minimum and maximum state of charge, SOC_{min} and SOC_{max}, respectively:

$$SOC_{\min} \le SOC \le SOC_{\max} \qquad (6)$$

E. Model validation

All components used in the simulation model are compared and validated with HOMER. Figure 2 shows validation results for the produced solar, wind and diesel energy for every month under the load following strategy. The simulations results are in good correspondence with HOMER results.

The cycle charge control strategy has a slightly different implementation than the HOMER implementation. The further validation of this strategy is discussed in the complete thesis.

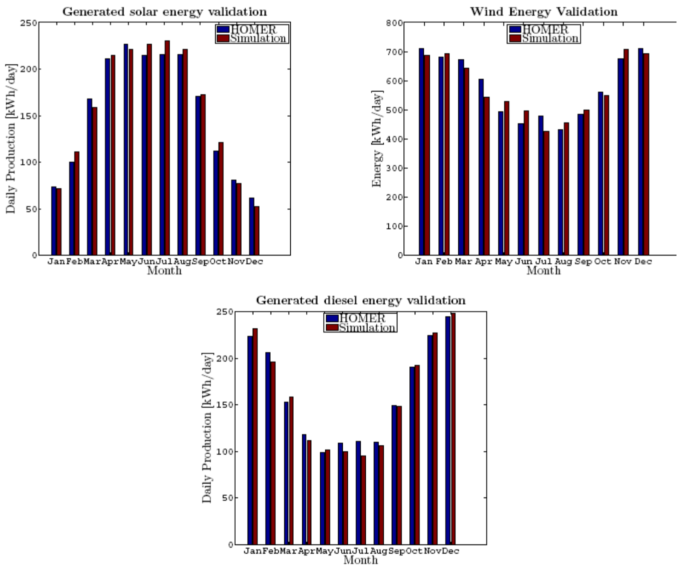

Fig. 2. Validation results using HOMER.

III. OPTIMIZATION PROCEDURE

In this section, the optimization procedure used to optimize a hybrid energy system is presented. In fact, the tilt angle of the solar panels is firstly optimized. After carrying out the optimization, a variability analysis is made. This analysis checks the obtained solution over multiple years which ends up with a confidence interval of the mean value of all resulting parameters. In this study, we use genetic algorithm technique. In fact, the genetic algorithm seems to be the best optimization algorithm for the current optimization study. This algorithm has an efficient performance for finding the global optimum and is suitable for complex problems [2].

The objective function of the hybrid system optimization procedure has the following form:

$$Total\_yearly\_\cos t = fuel\_\cos t + (start\_penality * \\ \#of\_starts) + emission\_\cos t + \sum_{c=1}^{c} \frac{installation\_\cos t_c}{life\_time_c} + \\ violation\_penality \tag{7}$$

with C being the set of all components in the model and the start/stop penalty applied to the diesel generator only. The optimization procedure for the tilt angle uses the same genetic algorithm but takes the total solar radiation output (I_T), which is calculated according to [2], as objective function:

$$Total\_yearly\_radiation = \sum_{n=1}^{N} I_{\tau,n} \tag{8}$$

with N being the total number of time steps.

IV. CASE STUDIES

In this section, we present the optimization results for four case studies, which have been chosen in such a way that they have totally different geographic and meteorological conditions. Each case study represents a small village with certain fixed number of population. These villages are not connected to the electrical grid, and the aim is to provide them by electricity via an optimal stand-alone hybrid renewable-conventional power plant.

For the sake of comparison, the annual load curves are kept constant for all case studies with the daily pattern shown in figure 3.

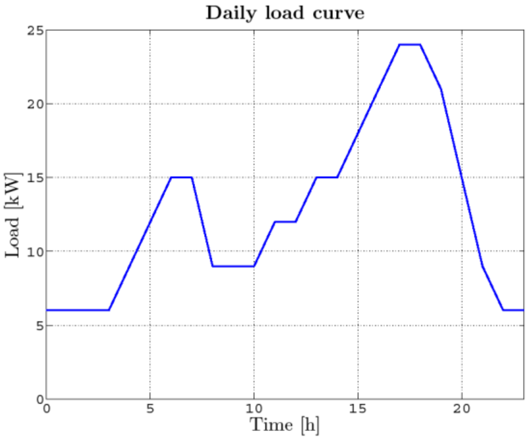

Fig.3. Daily load curve without added variability.

The first case study is to feed a fictive village at Ghent in Belgium. The second case study is at Oslo in Norway, while the third location is at Cairo in Egypt. Finally, the last case study is at Kinshasa, the capital of Democratic Republic of Congo.

At all locations, an optimization problem is solved to find the optimal sizing of the hybrid power plant, while eight parameters are obtained for each case study:

1. The battery capacity [kWh]
2. The rated diesel power [kW]
3. The rated inverter power [kW]
4. The rated rectifier power [kW]
5. The installed PV-power [kW]
6. The number of wind turbines installed
7. The rated power for each wind turbine [kW]
8. The type of controller strategy

The used parameters for the optimization of all case studies are shown in table 1. For the last 3 cases the maximum capacity shortage is reduced to 0.01% which results in a more complex system with the installation of a diesel generator. The last case uses the cycle charge strategy instead of the load following strategy.

TABLE I
INSTALLATION AND UPKEEP COST FOR BELGIUM CASE STUDY-A

Installation costs				
	Installation cost		Lifetime	
Battery bank	160	$/kWh	10	year
Diesel generator	1500	$/kW	20	year
Inverter	550	$/kW	10	year
Rectifier	50	$/kW	10	year
PV-Installation	4400	$/kW	20	year
Wind Turbine	--	$/kW	20	year
	Installation cost		Rated power	
Wind turbine	2000	$/kW	1	kW
	1560	$/kW	18	kW
	980	$/kW	850	kW
	900	$/kW	1500	kW
Fuel/Penalty cost				
Hourly fuel consumption			3.979	L/h/kW
Load fuel consumption			0.023	L/kWh
Fuel price			0.68	$/L
CO_2 emission penalty			6	$/ton
Start/stop penalty			1	$
Control strategy		Load following		
Maximum capacity shortage		1 %		

An example of the convergence of the objective function to a global minimum is shown in figure 4. In most cases the convergence takes longer than just 15 generations as stated in [8]. In this study, a total number of 30 generations is assumed to be sufficient.

The resulting systems are shown in tables 2 for Belgium, 3 for Norway, 4 for Egypt and 5 for Congo case study. No diesel generator is installed in the first case because of the shortage allowance of 1 %. The other systems are well designed with a diesel generator and renewable energy sources according to the applicable weather conditions.

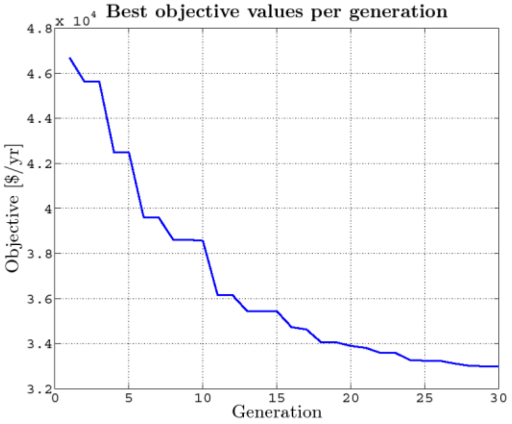

Fig. 4. The convergence of the objective function (Congo case study).

TABLE II
OPTIMIZED PARAMETERS FOR BELGIUM CASE STUDY

Optimized parameter	Value	
The battery capacity	269	kWh
The rated diesel power	0	kW
The rated inverter power	50	kW
The rated rectifier power	0	kW
The installed PV-power	0	kW
The number of wind turbines installed	1	
The rated power for each wind turbine	64	kW
Total yearly cost	1194	$/year

TABLE III
OPTIMIZED PARAMETERS FOR Norway CASE STUDY

Optimized parameter	Value	
The battery capacity	411	kWh
The rated diesel power	16	kW
The rated inverter power	47	kW
The rated rectifier power	0	kW
The installed PV-power	25	kW
The number of wind turbines installed	1	
The rated power for each wind turbine	106	kW
Total yearly cost	3377	$/year

TABLE IV
OPTIMIZED PARAMETERS FOR Egypt CASE STUDY

Optimized parameter	Value	
The battery capacity	347	kWh
The rated diesel power	12	kW
The rated inverter power	57	kW
The rated rectifier power	0	kW
The installed PV-power	22	kW
The number of wind turbines installed	1	
The rated power for each wind turbine	78	kW
Total yearly cost	2933	$/year

TABLE V
OPTIMIZED PARAMETERS FOR Congo CASE STUDY

Optimized parameter	Value	
The battery capacity	427	kWh
The rated diesel power	11	kW
The rated inverter power	54	kW
The rated rectifier power	55	kW
The installed PV-power	97	kW
The number of wind turbines installed	2	
The rated power for each wind turbine	1	kW
The state of charge set point	29	%
The minimum diesel running time	8	h
Total yearly cost	3423	$/year

In general, all optimized cases are feasible and are satisfying all predetermined constraints. But still small corrections can be made to further optimize the objective functions. These corrections have been studied and the results show a relative small impact on the objective function.

V. CONCLUSIONS

In this research work, the hybrid renewable-conventional electrical energy system was simulated, controlled and optimized. Based on four case studies, the developed optimization model was validated. Better system reliability, robustness and efficiency were achieved with the minimum total cost.

The proposed optimization study is definitely important for power system planning to maximize the system performance, as well as, minimizing the total cost. The performance and cost are highly dependent on the correct choice of all components sizing. We are convinced that the optimization procedure will guide the systems' designers into the right directions for every specific condition.

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VII. BIOGRAPHIES

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