OPTIMAL SIZING OF HYBRID ENERGY RESOURCES FOR ELECTRIFYING DISTANT RURAL AREAS OF IRAN

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ABSTRACT

Mathematical models are presented for PVs, wind turbines, battery storages and diesel generators for optimal in a hybrid isolated system. The optimization model is formulated and a case study is run in a ruralnon-electrified area of Iran.

INTRODUCTION

There are many far distant villages in Iran, where supplying them electricity via transmission systems is not cost-effective or even possible.
So, using renewable energy resources such as wind-power and photovoltaic remain as the only solution to supply energy to such areas. At the other side, there is an uncertainty in such natural resources which may cause lack of supply at special circumstances. That's why we suggest a more reliable resource as a redundant or complementary resource alongside these resources. Normally diesel generators are used in such cases, but considering the high costs of gasoil procurement and transmission to the site, the control strategy of the diesel generator is determined so to limit the use of it only to compensate for energy shortages.
This paper produces a method to optimize the size of photovoltaic, wind turbine, battery storage and diesel generator considering investment and maintenance costs, to electrify an existing village.
The case study is accomplished for a village in a high altitude area in Mazandaranan province of Iran.
An introduction will be made to the proposed system, then model equations will be presented for each system component. The objective function of the problem will be described after investigation of costs caused by each component. The objective function will be adapted for the optimization algorithm where the Genetic Algorithm is used for. Finally a case study is run in a real existing village in north of Iran.

SYSTEM MODELLING

The system which considered in this study consists of four major power sources: photovoltaic arrays, wind turbine generator, storage batteries, and a diesel generator (Fig. 1). Each component of the system is modelled as follows:

A. PV System

The output power of each PV array, with respect to the solar radiation power, can be calculated by "(1)" [1]:

$$P_{PV} = \frac{G}{100} \times P_{PV,rated} \times \eta_{MPPT} \quad (1)$$

where, G is perpendicular radiation at the arrays' surface (W/m^2), $P_{PV,rated}$ is rated power of each PV array at G=1000 W/m^2 and η_{MPPT} is the efficiency of PV's DC/DC converter and Maximum Power Point Tracking (MPPT).

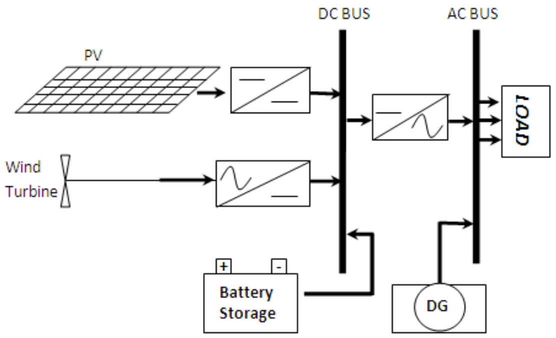


Figure 1. Block diagram of proposed hybrid system

B. Wind turbine generator

The outlet energy of a turbine could be calculated from its power-speed curve. This curve is given by manufacturer and usually describes the real power transferred from WG to DC bus. The model of WG is considered similar to that of BWC Excel-R/48 (see Fig. 2) [2]. The power of wind turbine is described in terms of the wind speed according to "(2)", by ref. [3].

$$P_{WT} = \begin{cases} 0 & v_W \le v_{ci}, v_W \ge v_{\infty} \\ P_{WT_{\max}} \times \left(\dfrac{v_W - v_{ci}}{v_r - v_{ci}} \right)^m & v_{ci} \le v_W \le v_r \\ P_{WT_{\max}} + \dfrac{P_f - P_{WT_{\max}}}{v_{co} - v_r} \times (v_W - v_r) & v_r \le v_W \le v_f \end{cases} \quad (2)$$

Where $P_{WT_{\max}}$ and P_f are WTs output power at rated and cut-out speeds, respectively, v_r, v_{ci}, and v_{co} are rated, cut-in, and cut-out speeds respectively, v_W is the wind speed at wind turbine hub elevation, and *m* is taken equal to 3 according to [1].

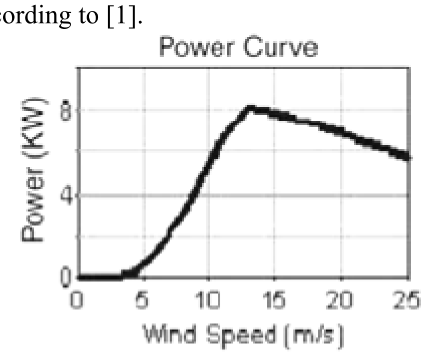


Figure 2. Power output characteristic of BWC Excel R/48 versus [4]

C. Battery storage

Most batteries used in hybrid systems are of deep-cycle lead-acid type. There are several other appropriate types (nickel-cadmium, nickel-iron, iron-air and sodium-sulphur) but these are generally either too expensive or too unreliable for practical application as most of them are still in the experimental stage.

The lead acid battery is widely used and, although complex, is well known [5].

A battery storage system may be presented as a voltage source E_{bat} connected in series with capacity C_{bat}, which represents the storage capacity of the battery, and a resistance R_b supposed constant during the operations of the charge and the discharge.

When the voltage V_{dc} is less than E_{bat}, the current is provided by the battery (I_d). In the contrary case, the current is received (Ic) [6].

The power input to the battery bank, is controlled by the equation $\Delta P(t) = PP(t) - PL(t)$ in which $P_P(t) = P_{PV}(t) + P_{WT}(t)$ is the total power produced by both PV panels and wind turbines at hour t and $P_L(t)$ is the power demanded by the load. It is evident that the power generated by the hybrid system and the amount of energy stored are time dependent. For the charging process of the battery, $P_P(t)>P_L(t)$, the state of charge (SOC) can be calculated from the following equation[[6]:

$$SOC(t+1) = SOC(t) + \eta_{BAT} \cdot \left(\left(P_L(t) - P_t(t) \right) / U_{BUS,nom} \right) . \Delta t \qquad (3)$$

For the discharging process, $P_P(t)<P_L(t)$, the SOC may be calculated as follows [6]:

$$SOC(t+1) = SOC(t) - \left(\left(P_L(t) - P_t(t) \right) / U_{BUS,nom} \right) . \Delta t \qquad (4)$$

where η_{BAT} is the battery charge efficiency is set equal to the round-trip efficiency and the discharge efficiency is set equal to 100% [7] and $U_{BUS,nom}$ is the nominal DC bus voltage (v).

For longevity of the battery bank, the maximum charging rate, SOCmax, is given as the upper limit, it is equal to the total nominal capacity of the battery bank [6].

D. Diesel generator

The diesel generator is modelled as a energy conversion system from fossil fuel to electricity with a conversion efficiency of η_{DG}, so it can be described by the following equations:

$$E_{DG} = \eta_{DG} \times E_{ff} \qquad (5)$$

where E_{ff} is the total energy content of gas-oil which is roughly proportional to the volume of gas-oil.

FORMULATING THE PROBLEM

The sizing problem solving needs minimization of the total cost of the total system while demanded load and total energy consumption is met. The diesel generator system is used as a redundant system to serve in other resources shortages. The optimization problem is formulated as follows:

$$C_{sys} = \sum_{i=1}^{ny} kt_i . C_{O\&M,DG} + CC_{DG} . P_{DG} + \sum_{i=1}^{ny} kt_i . C_{O\&M,BAT} + CC_{BAT} . P_{BAT} + CR_{BAT} + CC_{PV} . P_{PV} + CC_{WT} . P_{WT} \qquad (6)$$

where $C_{O\&M,DG}$ and $C_{O\&M,BAT}$ are the operation and maintenance costs of diesel generator and battery storage (USD), respectively, CC_{DG}, CC_{BAT}, CC_{PV} and CC_{WT} are the investment costs for diesel generator, battery storage, PV and wind turbine (USD/kW), respectively, *ny* is the number of years in which the economical analysis/decision will be made, CR_{BAT} is the replacement cost of the batteries, and kt_i is an economical factor to convert operational costs to present time value and is calculated as follows:

$$kt_i = \frac{1 + InfR}{1 + IntR} \qquad (7)$$

where *InfR* is the inflation rate and *IntR* is the interest rate. Operational costs of the diesel generator include procurement and transmission of gas-oil to the target site which is a function of electrical energy produced by the diesel generator:

$$C_{O\&M,DG} = \sum_{i=1}^{ny} \sum_{j=1}^{8760} P_{DG_{i,j}} . UNITCOST \qquad (8)$$

System constraints

The objective function is subjected to some constraints which guarantee the continuity of power and energy at minimum costs;

$$\sum_{i=1}^{ts-1} P_{BAT} . t_i \geq P_{BAT} . ts \qquad (9)$$

where *ts* is the present time of optimization in each snapshot. This constraint guarantees that the battery is always charged before being used as energy resource. P_{BAT} can take negative or positive values depending on the state of the battery (charge or discharge).

There is another constraint;

$$P_{PV,i} + P_{WT,i} + P_{BAT,i} + P_{DG,i} \geq P_{load,i} \qquad (10)$$

where $P_{load,i}$ is the power of load in the i^{th} time interval.

ADAPTION OF PROBLEM TO GA ALGORITHM

The non-linear optimization problem is solved by use of genetic algorithm where 100 initial chromosomes are generated. Each chromosome describes the value of each resource at any time interval of the search space. Mutation and cross-over are used to increase search depth.

CASE STUDY

A far distant village in north of Iran named Imamzade Yahya was selected for the case study. The village was not electrified at the time of investigation. The selection was made based on criteria such as distance, impassability, the number of permanent inhabitants and availability of sufficient wind and sunshine.

Some measurements have been made to check the availability of wind and solar radiation in the area. The average cloudy days were 2 days a week.

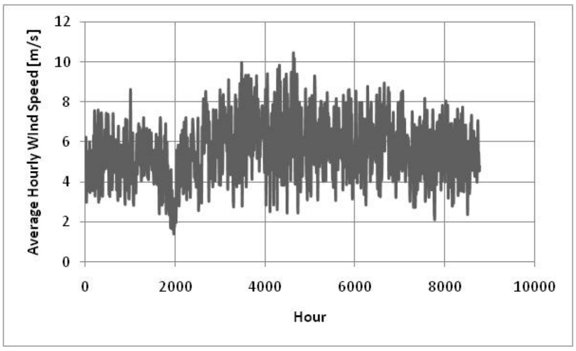
The other data used for the optimization are listed in table 1.

Table 1. Case data

System Parameter	*Value*	*Unit*
No. of customers	20	Nos.
Energy consumption	9	kWh/customer
Peak power	1.5	kW/customer
Inflation rate	15	%
Interest rate	11	%
ny	20	Years
Battery lifetime	4	Years
WT lifetime	20	Years
PV lifetime	20	Years
Average solar radiation (G)	3000	W/m^2
Rated wind speed	12	m/s
Cut-in wind speed	3	m/s
Cut-out wind speed	25	m/s
Gas-oil cost (including transmission costs)	0.7	$/kWh
Unit cost of PV	2500	$/unit
Unit cost of WT	3100	$/unit
Unit cost of battery	650	$/kwh
Unit cost of DG	350	$/kWh
Replacement Cost of battery	380	$/kWh

Figure 3 shows the wind speed measurement results at the desired elevation during a year.

Figure 3. Average hourly wind speed in one year measurement



Optimization results

Optimization has been made on the proposed objective function using a self developed code. Results show that the size of the diesel generator must be as large as to meet all load demand but not operated most of the times. It is accurate considering that the operational cost of diesel generator is relatively high but the investment cost is much less. So the algorithm decides to use the diesel generator as a back-up system for supplying electricity to customers.

Table 2 shows the optimization result. Figures 4, 5 show the battery reserve and the probable generation of the diesel generator according to measurement results.

Table 2. Optimal size of hybrid resources

P_{PV} [kW]	P_{WT} [kW]	P_{BAT} [kW]	E_{BAT} [kWh]	P_{DG} [kW]
19.8	14.6	24	120	30

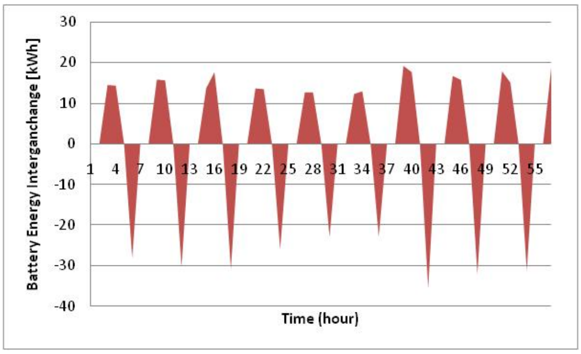


Figure 4. Battery power during first 72 hours (P<0: Discharge state)

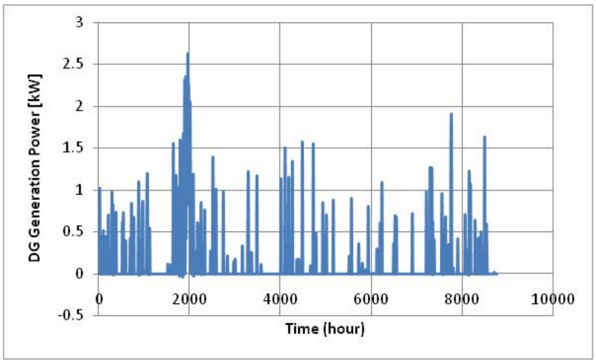


Figure 5. Power generation of diesel generator during a year with probable wind speed distribution similar to that of the measurement

CONCLUSION

Modelling of PVs, wind turbines, battery storages and diesel generators were modelled for optimal sizing. An objective function was developed for optimal sizing of these resources in a hybrid micro-grid where PVs, wind turbines and battery storages are going to be used as the

power source and a diesel generator is used for contingencies or conditions which the uncertain resources of wind and PV to some extent are lacked.
A case study with real data shows considerable results.

REFERENCES

[1] F. Jahanbani, G. Riahy, M. Abedi, "Design of an optimum hybrid renewable energy system considering reliability indices", Proceedings of ICEE 2010, May 11-13, 2010

[2] R. D. Lopez, J. L. Bernal-Agustin, "Multi-objective design of PV–wind–diesel–hydrogen–battery systems", Renewable energy 33, 2008,pp 2259-2572.

[3] S. M. Hakimi, S.M. Moghaddas-Tafreshi, "Optimal sizing of a stand-alone hybrid power system via particle swarm optimization for Kahnouj area in south-east of Iran," Renewable energy 34, 2009, pp 1855-1862.

[4] B. S. Borowy, Z. M. Salameh, "Methodology for optimally sizing the combination of a battery bank and PV array in a wind/PV hybrid system", IEEE Transactions on Energy Conversion, Vol. 11, No. 2, June 1996.

[5] Seeling-Hochmuth G. "Optimisation of hybrid energy systems sizing and operation control", A Dissertation in Candidacy for the Degree of Dr.-Ing, University of Kassel, October 1998.

[6] R. BELFKIRA, O. HAJJI, C. NICHITA, G. BARAKAT, "Optimal sizing of stand-alone hybrid wind/PV system with battery storage", Power electronics and applications, 2007 European Conference

[7] Borowy B. S., Salameh Z. M. "Methodology for optimally sizing the combination of a battery bank and PV array in a Wind/PV hybrid system", IEEE Transactions on Energy Conversion June 1996 Vol 11, no 2.