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EFFECT OF DISPATCH STRATEGY ON THE PERFORMANCE OF HYBRID WIND-PV-BATTERY-DIESEL-FUEL CELL SYSTEMS

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ABSTRACT

This paper presents a variety of dispatch strategies for hybrid renewable systems including wind turbine, PV panel, fuel cell, and diesel generator and battery bank. These strategies are distinguished based on the priority of the usage of battery bank, fuel cell and diesel generator in case of power deficit and the precedence of charging of battery bank and filling the hydrogen tank. For a given system, resource and load profile, the performance of the system corresponding to each dispatch strategy is evaluated against both cost related and reliability related measures. It is found that the performance of the system is highly under the influence of the dispatch strategy incorporated in the system. Therefore, in sizing hybrid renewable energy systems, dispatch strategy should be also considered as a decision variable that needs to be found along with the optimum size of other components of the system.

INTRODUCTION

Hybrid renewable energy systems (HRES) have a high scope due to their capability to meet the electricity demand in a reliable and environmental friendly way for both grid connected and standalone applications [1-9]. In case of standalone hybrid systems, the performance of the system is measured based on both the cost of the generated energy and the reliability in the power supply. The stochastic nature of renewable resources affects the reliability of standalone renewable systems. In order to increase the reliability, storage and backup components, such as battery bank, fuel cell and diesel generator, can be added to the system. A dispatch strategy for managing the usage and charging of storage and backup components is needed to be implemented in the system when more than one of these components is included in the system configuration.

Twelve different dispatch strategies can be used in a wind-PV-battery-fuel cell-diesel system as shown in Table 1. For these systems, six separate usage and two separate charging scenarios can be defined. In Table 1, B, FC and D stand for battery bank, fuel cell and diesel generator respectively.

In case of wind-PV-battery-diesel and wind-PV-battery-fuel cell configurations, the common practice is to use the battery bank first in precedence of diesel or fuel cell to cover for the power deficit [10-12]. In case of wind-PV-battery-fuel cell-diesel configuration, there is no study yet on the best dispatch strategy.

TABLE 1-CHARGING AND USAGE SCENARIOS

Dispatch Strategy	Usage Precedence	Charging Precedence
1	B-FC-D	B-H
2	B-D-FC	B-H
3	FC-B-D	B-H
4	FC-D-B	B-H
5	D-B-FC	B-H
6	D-FC-B	B-H
7	B-FC-D	H-B
8	B-D-FC	H-B
9	FC-B-D	H-B
10	FC-D-B	H-B
11	D-B-FC	H-B
12	D-FC-B	H-B

This paper investigates the effect of each one of these strategies on the cost- and reliability-related performance measures for a typical hybrid system.

HRES PERFORMANCE

Evaluation of the performance of HRES can be carried out considering various reliability measures, such as, unmet load, blackout distribution and mean time between failures as defined as follows.

Unmet load is the ratio of non-served load to the total load of that period of time. It is defined as [13],

$$U = \frac{1}{8760}\sum_{i=1}^{8760}\left(1-\bar{P}_{h,a}/\bar{L}_h\right)_i \tag{1}$$

where, $\bar{L}_h$ is the hourly-averaged load and $\bar{P}_h$ is the hourly averaged usable available power with period of analysis of T= 1 year=8760 h.

Total unmet load is total non-served load defined as [13],

$$U_t = U\sum_{i=1}^{8760}\left(\bar{L}_h\right)_i \tag{2}$$

where, P_a and L are, respectively, the usable available power and the demand load ($0 \le P_a \le L$). Usable available power is defined as:

$$P_a = \min\{P_{t,a}, L\} \tag{3}$$

in which, $P_{t,a}$ stands for the total renewable and non-renewable available power.

Total, maximum and average blackout durations are three parameters that indicate the system downtime periods due to power deficiency irrespective of the amount of unmet load. In contrast to the unmet load, assessment of design candidates based on blackout duration allows performing customer-need driven designs. Using an hourly-averaged data, total blackout duration is defined as [13]:

$$BO_t = \sum_{i=1}^{8760}\max\left\{0, sign\left(1-\left(\bar{P}_{h,a}/\bar{L}_h\right)_i\right)\right\} \tag{4}$$

where, $sign(\cdot)$ is the sign function. The information that can be extracted from the blackout distribution, such as the maximum blackout duration (the longest continuous blackout) $BO_{\max}$ and the average blackout duration BO_{av} (the average duration of each blackout), also can play an important role in evaluation of the system performance.

Mean time between failures (MTBF) is another reliability measure which is defined as the duration of the successful system operation over a period of time divided by the number of failures during that period. If the successful system operation is defined as the case when available usable power is greater than or equal to the load ($P_a \ge L$), using hourly-averaged quantities, the $MTBF$ defined as [13]:

$$MTBF = \frac{\sum_{i=1}^{8760}\max\left\{0, sign\left(\left(\bar{P}_{h,a}/\bar{L}_h\right)_i - 1\right)\right\}}{n_{fail}} \tag{5}$$

where, n_{fail} is the number of blackout occurrences during period T =8760 h.

Using hourly-averaged values for the demand load and renewable resources, levelised cost of energy LCE for a standalone HRES can be calculated as follows:

$$LCE = \frac{C_a}{\sum_{j=1}^{8760}\min\left\{\bar{P}_h, \left(\bar{L}_h + \bar{P}_{h,B,Charg} + \bar{P}_{h,H_2Tank}\right)\right\}_j} \tag{6}$$

in which C_a is the present value of the annual cost, $\bar{P}_h$ and $\bar{L}_h$ are, respectively, the hourly-averaged power and demand load, $\bar{P}_{h,B,Charg}$ and $\bar{P}_{h,H_2Tank}$ stand for the hourly-averaged power used to charge the battery bank and filling in the hydrogen tank. For detailed HRES cost modelling refer to [5], [6] and [13].

POWER MODELLING

This section describes the power modelling of the hybrid systems of Figure 1. The power output of the PV panels is given by [13]

$$P_{PV} = IA_{PV}\eta_{PV} \tag{7}$$

in which, I is the solar irradiance, η_{PV} is the overall efficiency of the solar panels and A_{PV} is the area of the solar PV panels. The power output of the wind turbine generators is given by [14]

$$P_{WT} = \tfrac{1}{2}\rho V_{hub}^3 A_{WT} C_p \eta_{EG} \tag{8}$$

where, ρ is the density of air, A_{WT} is the rotor area, η_{EG} is the overall efficiency of the electrical components and the gear box and C_p is the rotor power coefficient. More details on C_p model can be found in [13].

State of the charge (SOC) of the battery bank at the end of period is Δt given by [7]

$$SOC_{t+\Delta t} = SOC_t(1-\delta) + \frac{\left(\bar{P}_{\Delta t,R} - \bar{L}_{\Delta t}\right)\Delta t}{n_B c_B V_B}\eta_B \tag{9}$$

$$SOC_{\min} \le SOC_{t+\Delta t} \le SOC_{\max} \tag{10}$$

where, δ is the self-discharge rate of the batteries and c_B , V_B and η_B are the unit nominal capacity, battery bank voltage and the efficiency of the battery in charging/discharging states respectively. In this equation, it is assumed that the converter efficiency is close to unity.

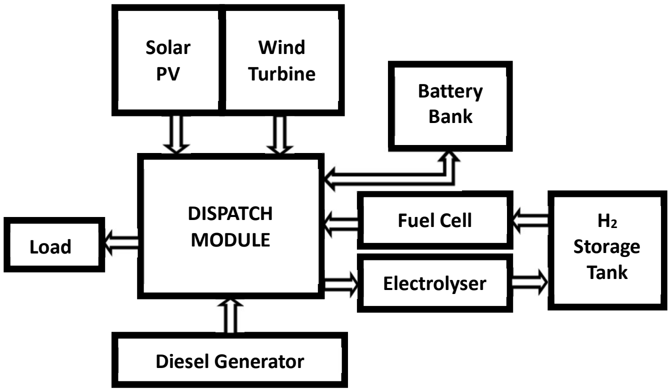

FIGURE 1- WIND-PV-BATTERY-FUEL CELL-DISEL HRES

The required power to reach the SOC of the battery bank to its maximum value $\overline{P}_{B,c}$ can be calculated by the following equation, in which $\eta_{B,c}$ is the charging efficiency and n_B is the number of batteries in the battery bank.

$$\overline{P}_{B,c} = \frac{(SOC_{\max} - SOC_t) n_B c_B V_B}{\Delta t \eta_{B,c}} \tag{11}$$

The extractable power stored in the battery bank, $\overline{P}_{B,av}$ can be calculated by the following equation, in which $\eta_{B,d}$ is the discharging efficiency.

$$\overline{P}_{B,av} = \frac{(SOC_t - SOC_{\min}) n_B c_B V_B \eta_{B,d}}{\Delta t} \tag{12}$$

In HRES applications the fuel used for fuel cell is normally hydrogen and the oxidant is the oxygen in the air. The fuel cell is used as a back-up storage system, which runs with the stored hydrogen, produced by the electrolyser during power excess of renewable sources. The nominal power of the fuel cell $P_{fc,nom}$ is the design parameter of the fuel cell. The maximum power that can be delivered by the fuel cell, $P_{fc,av}$ at time t, depends on the nominal power of the fuel cell and the available fuel in hydrogen tank [6]:

$$P_{fc,av}(t) = \min \left\{ \begin{matrix} P_{fc,nom} \\ (M_{tank}(t) - M_{tank,\min}) \dfrac{m_{H_2} LHV \eta_{fc}}{\Delta t} \end{matrix} \right\} \tag{13}$$

In Equation 13, $M_{\tan k(t)}$ is the available mass of the hydrogen tank at time t, $m_{H_2} = 2.016$ g/mol is the molar mass of the hydrogen, $LHV = 33kWh/kg$ is the lower heating value of hydrogen and η_{fc} is the efficiency of the fuel cell which normally varies between 40% and 60% [14].

The electrolyser is used for producing hydrogen from water and filling the hydrogen tank at the time of power excess. The power required by the electrolyser to fill the hydrogen tank P_{elec} is:

$$P_{elec}(t) = \min \left\{ \begin{matrix} P_{elec,nom} \\ (M_{tank,\max} - M_{tank}(t)) \dfrac{m_{H_2} LHV}{\Delta t \eta_{elec}} \end{matrix} \right\} \tag{14}$$

where, $P_{elec,nom}$ stands for the nominal power of the electrolyser, η_{elec} is the electrolyser efficiency, which is taken as 74% [6] in this study.

The power excess that comes from the renewable sources can be stored in the form of hydrogen in the hydrogen tank. The mass of hydrogen stored in the hydrogen tank after $\Delta t = 1hr$ of charging or discharging is given by Equations 15 and 16 respectively:

$$M_{tank}(t+1) = M_{tank}(t) + \frac{P_{elec} 3600 \Delta t}{2 V_{fc} F} \tag{15}$$

$$M_{\tan k}(t+1) = M_{\tan k}(t) - \frac{P_{fc,av} 3600 \Delta t}{2 F V_{fc}} \tag{16}$$

where V_{fc} and F are the fuel cell output and the Faraday's constant [6, 14].

RESULTS AND DISCUSSION

As mentioned earlier there are 12 distinct dispatch strategies for wind-PV-battery-fuel cell-diesel configuration. In the case of power excess, the power excess is used to charge the battery bank ($SOC_{t+\Delta t} \geq SOC_t$) and/or the hydrogen tank ($M_{\tan k(t+\Delta t)} \geq M_{\tan k(t)}$) based on the charging precedence set in the dispatch strategy. In case of power deficit, the power difference is covered by a combination of battery bank, fuel cell and diesel generator based on the usage precedence set in the dispatch strategy.

For the given resource and load demand in [13], the hybrid system of Table 2 is considered as the case study for investigating the effect of dispatch strategy on the performance of the system. In analysis, the following parameters are used. The overall efficiency of the electrical and mechanical components of wind turbine is taken as 90%, the site surface roughness length is taken as 0.03 m and the hub elevation $h_{hub} = 12m$. The efficiency of the PV panels in this analysis is 14%, the nominal capacity of the battery bank used is 40Ah per unit battery and the voltage of the battery bank used is 24V. The maximum and minimum SOC of the battery bank are 1 and 0.5 respectively, and the self-discharge rate is 0.002. The efficiency of the battery bank in charging and discharging is taken as 90% and 95% respectively. The efficiency of the fuel cell and electrolyser are taken as 47% and 74% .

TABLE 2-SIZE OF SYSTEM COMPONENTS

WT rotor radius(m)	PV panel area (m^2)	No. of batteries	$P_{d,nom}$ (W)	$P_{fc,nom}$ (W)	$P_{elec,nom}$ (W)
7	60	40	5000	10000	10000

Table 3 shows the system cost-related performance measures, LCE and total lifespan cost (TLSC) as well as reliability-related performance measures, total, average and maximum blackout duration, unmet load and mean time between failures for each dispatch strategy.

TABLE 3- SYSTEM PERFORMANCE

Dispatch Strategy	TLSC ($)	LCE (cent/kWh)	BO_t (hr)	BO_{av} (hr)	BO_{max} (hr)	Unmet Load (W)	MTBF (hr)
1	441000	76.1	0	0	0	0	8760
2	459000	79.3	0	0	0	0	8760
3	473000	83.2	274	1	2	745000	46
4	477000	83.3	92	1	1	448000	94
5	488000	84.3	0	0	0	0	8760
6	492000	85	0	0	0	0	8760
7	445000	77.6	91	1	1	443000	95
8	459000	79.3	0	0	0	0	8760
9	473000	83.6	274	1	2	946000	46
10	477000	83.7	92	1	1	649000	94
11	488000	84.3	0	0	0	0	8760
12	493000	85.2	0	0	0	0	8760

It can be observed that in most of cases, except cases 2, and 8 and cases 5 and 11, the performance measures change when different dispatch strategies are used.

For dispatch strategies in which diesel is used first (5, 6, 11 and 12), it can be seen that, irrespective of the order of the usage or charging of the other two components, the reliability is high (zero unmet load and blackout and highest possible MTBF). As expected, this is due to domination of diesel in power supply and charging. However, all these four systems have different LCE and TLSC.

Comparing strategies 1 and 7, which have the same usage order (battery first and fuel cell second) but with different charging order, it can be seen that the charging order affects both cost-related and reliability-related performance measures significantly. However, comparing strategies 3 and 9 with the same usage order (fuel cell first and battery second), the same conclusion cannot be drawn.

The performance of systems using the 2nd and 8th dispatch strategies seem exactly the same irrespective of the charging order. However, it should be noted that these performance measures are obtained deterministically and maybe different from the actual performances when considering the stochastic nature of renewable resources and the demand load as well as uncertainties in cost modelling [7, 14]. Using Monte Carlo simulation, the effect of uncertainties can be also included in the analysis. Here, the stochastic variations in wind speed, solar irradiance and the demand load are assumed to obey a normal distribution with standard deviations of 20%, 10% and 20% of the mean value respectively. Table 4 shows standard deviations in cost components assuming all having normal distribution variations. The standard deviation of the diesel fuel cost is also assumed to be 10% of the mean value. The standard deviation used for the efficiency of PV panels, fuel cell efficiency, electrolyser efficiency and wind turbine power coefficient model is 10%, 5%, 10% and 7% of the mean value respectively.

TABLE 4-STANDARD DEVIATION FOR THE COST COMPONENTS (% OF MEAN VALUE)

Standard deviation in cost components	WT	PV	BB	D	FC	E
Unit cost	10	10	10	10	10	10
Installation	5	5	0	0	0	0
Fixed O&M	5	5	5	5	5	5

Using Monte Carlo simulation with number of simulation of 100000, systems 2 and 8 are evaluated non-deterministically at a level of confidence of 99.99%. For more details on simulation steps see [7] and [13]. Table 5 shows how the performance of these two systems is different when a more realistic analysis is carried out.

TABLE 5-MONTE CARLO SIMULATION RESULTS

Dispatch Strategy	TLSC ($)	LCE (cent/kWh)	BO_t (hr)	BO_{av} (hr)	BO_{max} (hr)	Unmet Load (W)	MTBF (hr)
2	593000	102.4	1	1	1	0	8763
8	569000	98.3	92	1	1	3000	104

SUMMARY AND CONCLUSION

Both cost-related and reliability-related performance measures of a standalone HRES depend on the dispatch strategy incorporated in the system. In some cases, a deterministic analysis may lead to systems with different dispatch strategies but identical performance. However, it should be noted that deterministic analyses are not reliable and when a realistic stochastic analysis is carried out, the system performance will be different if different dispatch strategies are used. The optimum dispatch strategy depends on a number of parameters including the system configuration, system size, resources profiles and demand load profile. The optimum dispatch strategy, as a decision parameter, must be obtained as part of system configuration and size optimisation.

NOMENCLATURE

A	Area (m^2)
BO	Blackout Duration (hr)
C	Cost($)
c	Battery Capacity (Ah)
F	Faraday's Constant
I	Solar irradiance(W/m^2)
L	Demand Load(W)
LHV	Lower Heat value of Hydrogen
$MTBF$	Mean Time Between Failure
M	Mass of stored hydrogen (kg)
N	Life span
m_{H_2}	Molar mass of hydrogen(g/mol)
n_B	Number of Batteries in battery bank
P	Power (W)
SOC	State of Charge
U	Unmet Load
V_B	Battery Bank voltage
V_{fc}	Fuel cell voltage
z_0	site surface roughness
η	Efficiency
δ	Self-discharge rate
ρ	Air Density
σ	Standard deviation

Subscripts

a	Annual
av	Average; Available
B	Battery
c	Capital
D	Diesel
$elec$	electrolyser
F	fixed
fc	Fuel cell
h	Hourly
ins	Installation
max	Maximum
min	Minimum
nom	Nominal
$O\&M$	Operation and Maintenance
PV	Photovoltaic
R	Renewable
S	System
t	Total; Time
$tank$	Hydrogen tank
u	Unit; Uncertain parameter
V	Variable
WT	Wind Turbine

Abbreviation

BB	Battery bank
D	Diesel generator
E	Electrolyser
FC	Fuel cell
PV	Photovoltaic
WT	Wind Turbine

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