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Sustainable Power Supply Using Solar Energy and Wind Power Combined with Energy Storage

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Abstract

The idea of integrating intermittent sources of energy such as solar and wind with energy storage has several benefits for the electricity grid. The first benefit is that energy storage can help the grid during the periods that grid is facing high peak demand. The second benefit is that using energy storage would help shifting the grid load from peak and busy time to a less demand time. And the third benefit is that using energy storage would help smoothing the variations in power generation fed into the grid by variable and intermittent renewable resources. The third benefit is of particular important because in future more renewable energy sources will be integrated into the electricity grid worldwide. The objective of this paper is to present the results of a study conducted to examine the potential role and potential benefits of energy storage integrated into intermittent sources. Using energy storage will provide an opportunity to create a sustainable power supply, and to make the electricity grid more reliable especially with large proportion of grid-connected renewable sources.

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Keywords: solar, wind, storage, sustainable power supply

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1. Introduction

One of the aspects of the future electricity supply system is integration of renewable sources and better use of power produced by distributed generation technologies such as solar, wind, co-generation plants, and etc.

Because of intermittency nature of the solar energy and wind power and also because of sudden variations of the power produced by these intermittent sources, use of storage devices is essential. In this

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study a power system is proposed which consists of solar photovoltaic (PV), wind power and a storage system to make a mini grid. The system is to supply a sustainable power for loads connected to the mini grid.

For the purpose of system simulation, the solar PV system is modelled based on an *empirical* model, and wind power operating curve is simulated with *Weibull distribution and using Monte Carlo technique*. Both generators are of intermittent nature, so an energy storage technology is included to help power smoothing process of the grid.

2. Modelling Approach used in this study

In this study a power system consisting of a base-load generator, a solar photovoltaic (PV) and wind generator is investigated. The solar PV operating curve is constructed based on a mathematical model. For the purpose of simulating, the wind power operating curve is simulated with Weibull distribution. These two electricity generating units (solar and wind) are to supply a typical load with a peak time period. As both generators are of intermittent nature, this study will examine the potential role of batteries to help the grid. The amount of electric power supplied by batteries depends on number of batteries and level of charge and the capacity of each battery.

The total electricity supply from solar PV energy and wind power should balance the total demand for electricity therefore, to estimate the balance between demand and supply, an appropriate operational model of load, solar PV and wind generators will be required. Following section describes fundamental concept of each operation.

3. Operational model of base load

Base load includes power supply from coal-fired plant, supported by thermal power plants and gas turbines for the middle loads. In the simulation, the base-load operation was modeled as constant.

4. PV operation curve model

PV power strongly depends on the time of the day, level of the sun radiation and the weather conditions. In this study, the following empirical model was developed based on actual solar PV operation:

$$P_{PV} = a\,R^5 + b\,R^4 + c\,R^3 + d\,R^2 + e\,R^1 + f$$

R represents the sun radiation

Figure 1 shows operation model of solar PV in locations with clear sky. Figure 2 shows operation model of solar PV with fast moving clouds.

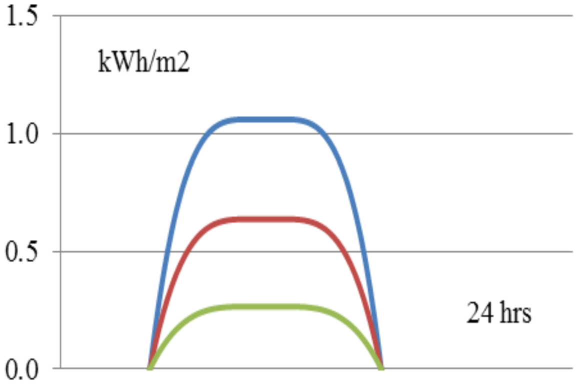

Figure 1 PV operational curve considering weather conditions

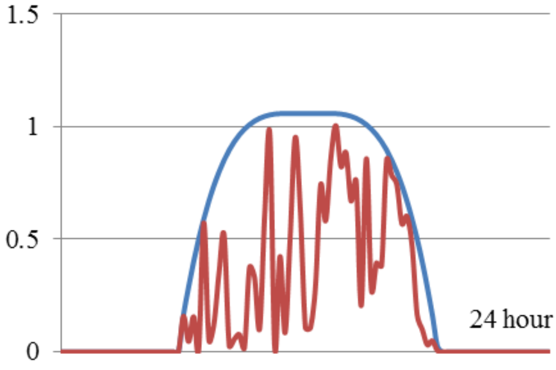

Figure 2 PV operational curves for fast moving cloud conditions

5. Wind speed model

The fact that wind power output varies is not really an issue if enough and accurate information is available in advance for predicting how much power a wind turbine or a wind farm will be producing at any given time. Accurate forecasting is an essential factor to a successful integration of wind power into the electricity grid.

Accurate operational modelling and power output estimation usually are carried out before a wind turbine is installed. Of course, there will be variations between forecast and actual information. Any power system is influenced by a large number of planned and unplanned factors, but they have been designed to cope effectively with these variations.

The other important factor is location, where a wind farm is built meaning availability of good wind resources.

Unlike large hydro and geothermal power stations that have little flexibility in their siting because of the nature of the resource, wind power can be developed in a very wide range of locations, and at many scales, from one to couple of hundreds wind turbines.

Choosing a good site can make a big difference to the power output from a wind turbine, and this is greatly magnified over a turbine's operating lifetime.

If site data is completely available, then by using hourly data for hours per year at each wind speed we can estimate power in the wind and the power delivered by using the Equation 1.

$$P_{Wind} = \tfrac{1}{2}\,\rho\, A\, V^3\, C_{p1} \,.\, C_{p2} \qquad (1)$$

Where A is the cross-sectional area of the individual wind turbine, ρ is the density of the air, C_{p1} is wind energy conversion efficiency (maximum 59%) and C_{p2} is the device efficiency, and V is the wind speed. It is assumed that hourly wind speed throughout the year is available.

If only the annual average wind speed is available, then we use Equation 2 to estimate the power in the wind and the power delivered by wind turbine.

$$P_{Wind} = \tfrac{1}{2} \,.\, 6/\pi \,.\, \rho\, A\, (V_{Ave})^3\, C_{p1} \,.\, C_{p2} \qquad (2)$$

Performance evaluation can also be estimated by using wind turbine power curve provided by the turbine manufacturer, in the presence of availability of wind data. In this case, for wind speeds within the range of V_{CI} and V_R, wind power is determined by the Equation 3.

$$P_{Wind}=P_R(V^3-(V_{CI})^3)/(Vr^3-(V_{CI})^3) \qquad (3)$$

- V_{CI}: cut-in wind speed
- $V_{R:}$: rated wind speed
- V_{CO}: cut-out wind speed
- The wind speed greater than cut-out speed power will be zero

Table 1 shows a wind turbine power output in terms of the wind speeds.

TABLE 1

Wind power	Wind speed
$P_{Wind}=0$	$0<V<V_{CI}$
$P_{Wind}=P_{Rated}(V^3-V^3_{CI}) / (V^3_r-V^3_{CI})$	$V_{CI} <V<V_r$
$P_{Wind}= P_R$	$V_r <V<V_{CO}$
$P_{Wind}= 0$	$V_{CO} <V$

In the absence of wind data, performance evaluation can be conducted by using Weibull probability density function or the Monte Carlo method.

6. Generating wind speed using Weibull PDF

For the purpose of describing the wind speed frequency distribution, there are several probability density functions available. The probability density functions determine the frequency distribution of wind speed and number of hours in one year that the wind turbine is operational at a certain wind speed. There are two probability density functions (PDF) that are most commonly used. These are Weibull and the Rayleigh PDF.

If site data are not completely available (but only annual average), we can use Weibull statistics with an appropriate shape parameter, and scale parameter to estimate the energy delivered.

A general expression that is often used for characterizing the statistics of wind speeds is Weibull Probability Density Function (PDF) expressed in mathematical form as shown in Equation 4.

$$f(v) = (k/c)\ (v/c)^{(k-1)}\ .\ \exp\left(-(v/c)^{k}\right) \qquad (4)$$

Where k is called the shape parameter, and c is called the scale parameter. Using site data and assuming Weibull statistics, with an appropriate shape and scale factor, we can estimate the power delivered. This has been shown in Figure 3.

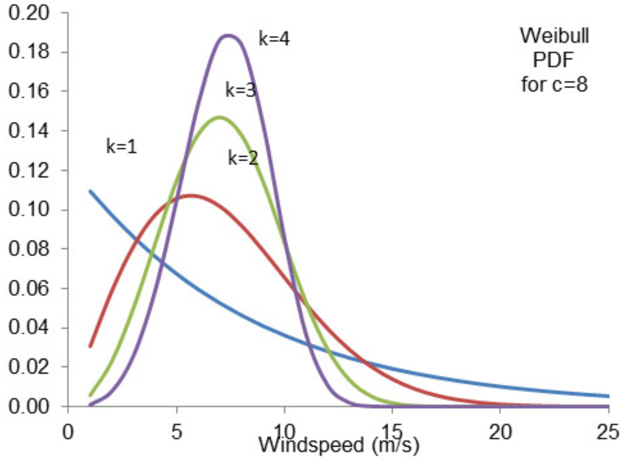

Figure 3, Weibull PDF for c=8 and k = 1, 2, 3, and 4

The other alternative for estimating the power delivered by wind turbine is the Rayleigh statistics.

The Weibull PDF for shape parameter k=2 the PDF is known as Rayleigh PDF shown in equation 5. If only average wind speed is available, then by using Rayleigh statistics we can estimate the power delivered.

$$f(v)=(2v/c^{2})\ .\ \exp\left(-(v/c)^{2}\right) \qquad (5)$$

$$\text{Average of wind speed } (V_{ave}) = \int 0\ v\ f(v).dv = (\sqrt{\pi}/2).c$$

$$(V_{ave}) = (\sqrt{\pi}/2).c \quad \text{and } c = 2\ V_{ave}/\sqrt{\pi}$$

This expression gives us the link between scale factor and average of wind speed.

To drive this expression all we need to do is to replace c in Equation 5 by its expression in terms of average wind speed.

The equation 6 is used to determine the probability of wind speed v and hours per year for a given average wind speed.

The expression that gives us the Rayleigh's PDF in terms of average wind speed is shown in equation6:

$$f(v) = (\pi\ v/2\ (V_{ave})^{2})\ \exp\ (-(\pi/4)\ (v/V_{ave})^{2}) \qquad (6)$$

Rearrangement of this Equation will give us the Equation 7.

$$V = 2\ .\ (V_{ave})\ /\ (\pi)1/2\ (\ -\ Ln(1-f(v)))^{1/2} \qquad (7)$$

7. Generating wind speed using Monte Carlo method

If site data are not completely available (but only annual average of wind speed is available), we can use Weibull statistics, shown in Equation 8, where X is a random number between zero and one.

$$V = 2\ .\ (V_{ave})\ /\ (\pi)1/2\ (\ -\ Ln(1-X))^{1/2} \qquad (8)$$

Figure 4 shows simulated wind speed, while figure 5 shows distribution of wind speed over one year

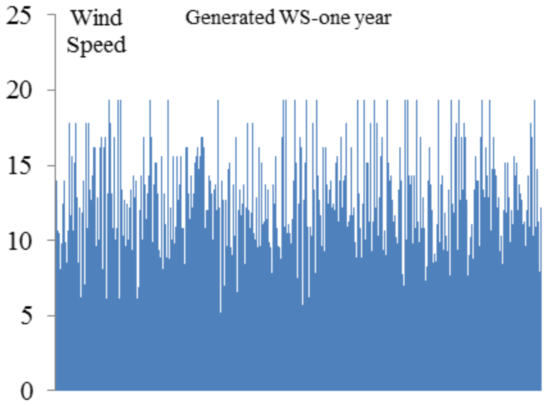

Figure 4 distribution of simulated wind speed using Monte Carlo method with Weibull PDF

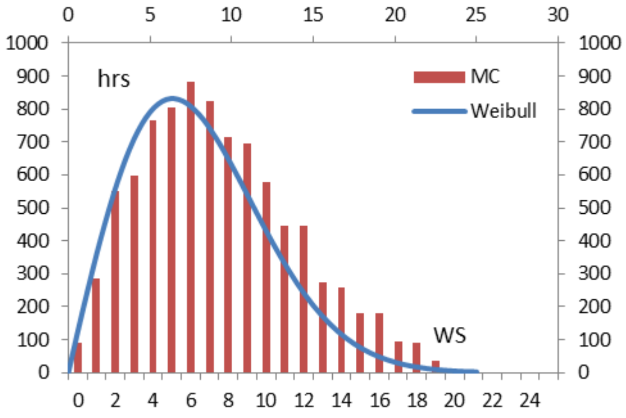

Figure 5 distribution of simulated wind speed

8. Simulation results

Usually, power demand varies considerably with time of the day and the season. The power generation mix in this study consists of conventional power generator for the base load, as well as renewable energy sources. The base load is operated under a constant output power, while variable renewable resources such as wind power and solar PV energy are associated with weather-related power output variations. Simulation results are shown in Figure 6.

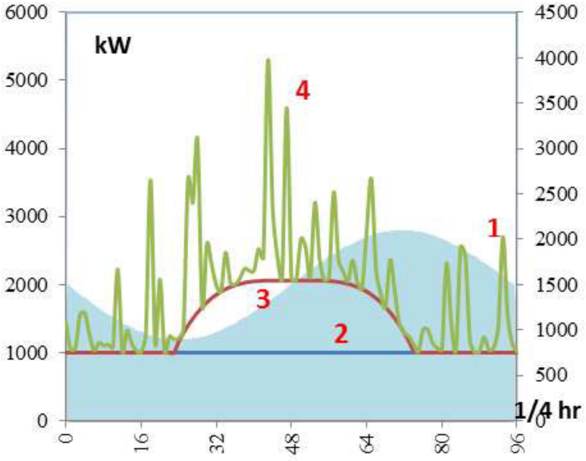

Figure 6 simulation results

In Figure 6 shaded area (1) represents the load in 24 hours with 15 minutes time intervals. The blue line (2) shows the constant base load generator. The red curve (3) line shows the solar PV generator, and green line (4) shows the wind generator. Storage device can absorb excess power during the low-demand period and release the power during peak-demand periods. Figure 7 shows balance of power without storage, while Figure 8 shows balance of power with storage.

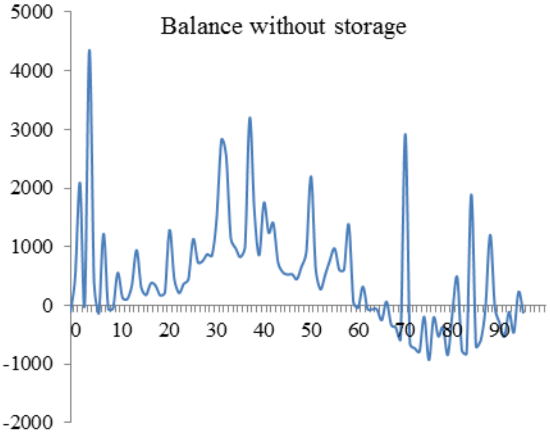

Figure 7 supply and demand balances without storage

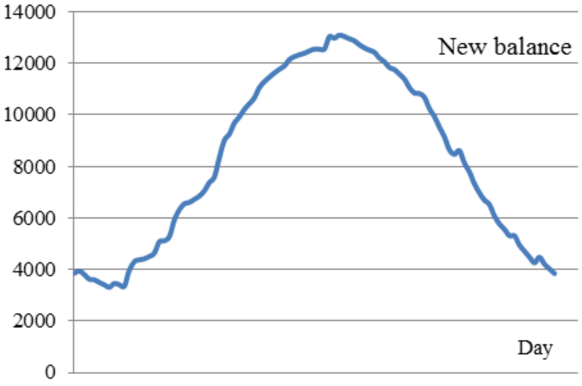

Figure 8 supply and demand balances with storage

9. Conclusions

This paper has presented the results of a study conducted to examine the potential role and potential benefits of energy storage integrated into intermittent sources. Using energy storage will help a better balance of power and provide an opportunity to create a sustainable power supply, and to make the electricity grid more reliable especially with large proportion of grid-connected renewable sources.

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