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Near-optimal standalone hybrid PV/WE system sizing method

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ABSTRACT

Standalone Hybrid Photovoltaic/Wind Energy (PV/WE) systems shall be sized for minimal cost, considering initial capital, continuous operational, and occasional maintenance costs, beside replacement costs over the life of the system. Two of the most utilized sizing techniques are critical month and algorithmic optimization. Critical month technique ensures energy supply without supply and demand (S & D) issues but at the expense of higher cost while algorithmic optimization requires complex mathematical formulations followed by synthesis of appropriate algorithm. This paper proposes a simple mathematical approach to size cost-effective near-optimal hybrid PV/WE system with battery energy storage (BES) and fossil fuel generator (FFG) without complex formulation and algorithm synthesis. Standalone Hybrid PV/WE system with BES and FFG is sized using proposed method and bench marked against a system in Homer Pro Microgrid Analysis Tool. Three systems are sized ranging from few kilo-watts (kW) to mega-watts (MW) in North America, Europe and Southeast Asia to validate proposed method universality.

1. Introduction

Exhausting fossil fuels (Shafiee and Topal, 2009), rising energy demand (International Energy Outlook, 2015), and global warming (Woodward, 2014) are causing tremendous interest in the renewable energy (RE). Conventional generation systems insufficiency and lack of access to power (World Energy Outlook, 2016), especially in remote areas (RA) coupled with continuously dropping prices of RE equipment are also advancing RE use. Wind and solar, frequently converted RE resources are transforming electrical power generation, distribution and utilization systems globally. Solar photovoltaic (PV) systems (PVS) require little to no maintenance, are easy to install, have no moving parts and make sense at all levels (smaller or larger) but expensive as compared to wind energy (WE) systems (WES). WES require expertise to operate and maintain and are cheaper only on a larger scale. Both PVS and WES require energy backup for reliable operation due to RE resources (wind and solar irradiance) inherent intermittency. Fossil fuel generator (FFG) and/or battery energy storage (BES) are usually employed to provide energy backup. FFG requires fuel and maintenance while battery storage is expensive with a shorter lifespan. Complimentary natures of PVS and WES can reduce impacts of intermittency due to weather, seasons, etc. (Gerlach et al., 2011) resulting in a smaller supply and demand (S & D) gap requiring smaller energy backup system.

Multiple orientations of PV array in terms of tilt (installation angle) and azimuth (East-West facing) can be used to cater PVS production to load, in addition to seasonal adjustments and single or dual axis tracking. Adjusting tilt twice a year (summer and winter) can increase production by ≈4% while dual axis up to 29% (Optimal Tilt of Solar Panels, 2016). But seasonal adjustment or tracking add cost with gain in production being the function of site latitude. In a similar fashion, WES installation at height increase WE production and can be used to increase WE production but at increased cost. Geographical dispersion also reduces intermittency (Marcos et al., 2012). Irrespective of solution employed, RE systems always require energy backup system (Ponoum et al., 2013) for reliable operation.

Cost effective and reliable systems implementation require careful investigation and sizing. Sizing PVS, WES or hybrid PV/WE systems is a mature subject and literature reports variety of optimization techniques to size hybrid systems (Zhou et al., 2010; Li et al., 2012; Kellogg et al., 1998; Borowy and Salameh, 1996; Habib et al., 1999; Shrestha and Goel, 1998; Yang et al., 2007; Maghraby et al., 2002; Diaf et al., 2008; Markvart, 1996; Koutroulis et al., 2006; Khatib et al., 2012; Vrettos and Papathanassion, 2011) beside critical month technique. Sizing in Zhou et al. (2010), Li et al. (2012), Kellogg et al. (1998) and Borowy and Salameh (1996) identify optimal configuration focusing minimum cost of the system with supply reliability by traversing all possible combinations of PVS, WES and BES. Li et al. (2012) propose complimentary PV/WE system with BES. They size WES and use it as a reference for searching optimal size of PVS to satisfy load. Once PVS is identified, BES is added to bridge the S & D gap due to intermittency. Kellogg et al. (1998) minimize system cost with 0% loss of load (LOL) on average,

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energy supply to load 100% of the time on average. Reference Borowy and Salameh (1996) uses WES as reference to run all combinations of PVS and BES for minimum cost and supply reliability. Habib et al. (1999) seek optimal % of RE power generated by hybrid PV/WE system to achieve optimal cost based on PV/WE ratio to provide fixed power. PV and BES systems ensuring S & D balance with varied % of LOL and minimum cost are reported in Shrestha and Goel (1998), Yang et al. (2007), Maghraby et al. (2002) and Diaf et al. (2008). Reference Yang et al. (2007) added orientation of PV arrays, height of WES, and capacity of BES, (Maghraby et al., 2002) defined minimum cost based on desired % of LOL, and (Diaf et al., 2008) brought levelized cost of energy into the optimization process. Varying PV/WE seasonal generations based sizing for minimum cost is proposed by Markvart (1996). Reference Koutroulis et al. (2006) minimizes 20-year total cost of hybrid PV/WE system with BES, taking PV orientation and WE height into account for 0% LOL. Khatib et al. (2012) has relied on LOL of up to 2.7% (10 days) per year. Reference Vrettos and Papathanassion (2011) is a grid tied system in which shortage is supplied by the grid.

In summary, optimal sizing methodologies (Zhou et al., 2010; Li et al., 2012; Kellogg et al., 1998; Borowy and Salameh, 1996; Habib et al., 1999; Shrestha and Goel, 1998; Yang et al., 2007; Maghraby et al., 2002; Diaf et al., 2008; Markvart, 1996; Koutroulis et al., 2006; Khatib et al., 2012; Vrettos and Papathanassion, 2011) generally, (1) did not take PV orientation, seasonal adjustment, tracking and WG installation height into account, (2) ignored FFG for backup, (3) focused RE and BES for 100% energy backup to ensure 0% LOL (100% supply), or (4) accepted % of LOL as a part of the solution. Number (1) resulted in missed production-catering to load possible with optimal PVS orientation, adjustment, tracking and WES installation height, (2) missed on possible lower system cost with FFG, (3) resulted in oversized system causing extra cost, and (4) compromised energy supply reliability.

This paper, proposes simple mathematical approach to size near optimal standalone hybrid PV/WE system with BES and FFG. The proposed methodology, (1) is extremely simple, (2) ensures zero S & D gaps, (3) uses BES with FFG, without limiting system configuration to BES alone for energy backup, and (4) considers PVS optimal orientation and WES height for installation to arrive at cost-effective near-optimal Hybrid PV/WE system. The rest of the paper is organized into the following sections: (2) RE Systems, (3) RE Systems Typical Sizing Methods, (4) Proposed Method to Size Near-Optimal Standalone Hybrid PV/WE Systems, (5) Sizing and Discussions and (6) Conclusions.

2. RE systems

Typical systems considered in this work consists of PVS, WES, BES and FFG. Therefore, this section introduces readers to these systems one by one for improved readability of the paper.

2.1. PV system (PVS)

PV system (PVS) convert solar irradiance into DC power using PV modules. Multiple modules are connected in series to build strings and strings in parallel to form PV array. PV array produce DC voltage and DC current, therefore, inverter is added to convert DC power into AC power for load and/or injection into grid.

Current and voltage produced by PVS depends on irradiance and temperature, in addition to the type and area of the cell used. The output voltage of PVS varies inversely with changes in temperature while output current directly with irradiance (light). Power produced by PVS at any instant t, as a function of light and temperature, is given by (1), where P_t, PVS_{ac}, G_t, G_{ref}, C_p and T_{ref} are actual power at time t with system operating temperature T_{sys}, ac power, solar irradiance at time t, reference solar irradiance, change in module power (P) in response to variations in temperature, and reference temperature, respectively. PVS_{ac} in (1) is given by (2), where E is the energy and PSH (peak sun hour) represents average number of hours in a day with 1000 W/m^2.

Table 1
10 kW PVS output as a function of azimuth (Toronto, Canada).

10 kW Rooftop PVS Potential				
Yield (kWh)	Loss (%)	T_s (deg)	A_s (deg)	Remarks
11,174	−15.4	0	0	Flat
7951	−39.8	37	135	North-East
10,370	−21.5	37	90	East
12,375	−6.3	37	45	South-East
13,204	0	37	0	South (Optimal)
12,522	−5.2	37	−45	South-West
10,596	−19.75	37	−90	West
8070	−38.9	37	−135	North-West
6863	−48	37	−180	North

$$P_t = G_t/G_{ref}\{PVS_{ac} + [PVS_{ac}C_p(T_{sys} - T_{ref})]\} \tag{1}$$

$$PVS_{ac} = E/PSH \tag{2}$$

PVS output gets affected by soiling, such as dirt and snow, reducing PVS output for up to 10%. Soiling losses (S_L) are higher in industrial areas as well as climates with heavy snow. Equipment mismatch and quality, modules light reflection and light induced degradation, DC and AC resistance, DC-DC and DC-AC conversion efficiencies (all collectively represented by (D_L)) also ad 10% of losses. Therefore, PVS is usually oversized by 120% to compensate for losses (S_L and D_L) and up to 140% for increased PV production.

PVS output gets affected by installation tilt (T_S) and azimuth (A_S). Table 1 shows output of the PVS as a function of azimuth for a 10 kW system using (PVSYST, 2016). Table 1 reveals that the best installation orientation for max energy production at this specific site in Toronto (Canada) is due south ($A_S = 0°$) at 37° tilt. Other orientations have lower overall production, however, they can be used to shift PVS production into the other times of the day, such as morning (A_S = East i.e. 90°), afternoon (A_S = SW i.e. −45°), etc., to cater production to increased consumptions in those timings. Table 1 also shows effects of tilt on production by comparing production at $T_S = 0°$ and $T_S = 37°$ (PVS production is approximately 1.15 times higher for 37° tilt as compared to 0°). PV systems may be installed at non-optimal tilts due to several reasons including roof pitch and wind load.

Sun travels higher in the sky in summer and lower in the winter, therefore, PVS production can be catered to summer or winter load by subtracting or adding X^o (X degrees) to optimal tilt, respectively. This causes lower tilt in summer and higher in winter to face sun for longer periods in those seasons. System with 2, 3 or 4 seasonal tilt adjustments (S_A) is also possible to maximize PV energy production to meet load in those seasons. Single (S_x) or dual (D_x) axis tracking PVS can also be used to increase production all year around but at increased cost.

2.2. Wind energy system

Wind Energy system (WES) generated power (P_W, wind power) is given by Eq. (3), where ρ, A, V, and C_p are air density, rotor blades swept area (A= πr^2), wind speed and turbine power co-efficient, respectively. C_p is the function of Tip Speed Ratio and Blades Pitch Angle. Maximum power extraction at all wind speeds V is made possible by adjusting Tip Speed Ratio and/or Blades Pitch Angle. Due to the cubic relationship between P_w and V ($P_w \propto V^3$), average wind speed does not provide accurate site potential but an estimate of the possible power production. A distribution of wind speed data over time is required for accurate estimation of site potential and shall be used, where available, when sizing WES (Woofenden, 2016).

$$P_W = 0.5\rho A V^3 C_p \tag{3}$$

Air-density (ρ), a function of elevation, temperature and weather fronts, can be represented by a constant for calculating or estimating wind power (Iowa Energy Center, 2017). Thus, (3) can be simplified as