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Method for planning a wind–solar–battery hybrid power plant with optimal generation-demand matching

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Abstract: This study aims to propose a methodology for a hybrid wind–solar power plant with the optimal contribution of renewable energy resources supported by battery energy storage technology. The motivating factor behind the hybrid solar–wind power system design is the fact that both solar and wind power exhibit complementary power profiles. Advantageous combination of wind and solar with optimal ratio will lead to clear benefits for hybrid wind–solar power plants such as smoothing of intermittent power, higher reliability, and availability. However, the potential challenges for its integration into electricity grids cannot be neglected. A potential solution is to utilise one of the energy storage technologies, though all of them are still very expensive for such applications, especially at large scale. Therefore, optimal capacity calculations for energy storage system are also vital to realise full benefits. Currently, battery energy storage technology is considered as one of the most promising choices for renewable power applications. This research targets at battery storage technology and proposes a generic methodology for optimal capacity calculations for the proposed hybrid wind–solar power system.

1 Introduction

Traditional power generation occurs in centralised power plants, which comprise of large power stations producing the bulk amount of power utilising fossil fuels. Usage of conventional fossil fuels has adverse effects on the environment in terms of carbon dioxide emissions and nuclear waste problems. Owing to the rapid rise in world's energy consumption and drop in fossil fuels, the development of renewable energy (RE) sources has emerged to be the most stimulating field of modern electrical engineering and technology. Reduced dependence on conventional fuels, improved energy security, and lowered emissions of greenhouse gases are some of the benefits offered by RE. Restructuring of electrical power systems is observed due to the increased use of renewables in the generation of electricity. Other important factors such as eco-friendly, economic profits, and technological advances in the distribution systems have motivated the increased use of renewable systems [1]. However, the harvest of RE on a large scale and achieving maximum permeation of RE sources in power systems is considered a cumbersome task. Several barriers have to be overcome by industry and researchers in the field of electrical engineering in order to tap the RE in an effective manner. There is an urgent need for innovative ideas in the field of RE so as to contribute to the development of this technology.

In recent years, the availability of solar panels at cheaper prices has contributed toward the emergence of solar photovoltaic (PV) power to be a leading incipient technology of RE domain [2, 3]. However, the integration of PV power into local power grids poses several challenges due to its intermittent nature. The problems encountered due to the use of solar power include generation of unwanted harmonics in the voltage and current, deviations of voltages in distribution feeders, and flickers. Thus, it is necessary to study the effects of PV penetration and discuss solutions so as to deliver solar power in a substantial amount at the highest possible reliability and efficiency at an affordable cost.

Similarly, the power obtainable from wind has also revealed a profligate growth rate [4]. However, the integration of wind power at local levels poses power quality, reliability, and protection issues which are required to be addressed in order to deliver efficient wind power at an affordable cost [5]. The operation of interconnected grids is also affected due to fluctuating power output of wind farms. Intermittent nature of wind power has limited its maximum penetration in electricity networks.

A proficient solution for the integration of RE sources into the electricity grid is the use of energy storage systems (ESSs) [6–11]. Several types of ESSs are available nowadays including battery energy storage, fuel cells, super capacitors, and flywheel-based storage systems [12–14]. Nonetheless, the affordability of these ESSs is still an area of concern (see, e.g. [11] and references therein). Among the available technologies, battery ESS (BESS) is considered as one of the most promising choices for RE systems. The working principle of a BESS is found on storing surplus energy in the periods of excess energy production as compared with the demand and feeding power back to the grid when needed. Thus, the renewable power system can be made more economical by optimising the cost and size of BESS. This can be achieved by: (i) selection of less expensive storage type; (ii) minimisation of storage size; (iii) and development of efficient dispatching procedures [15].

Determining optimal BESS capacity, however, is a challenging task due to the irregular nature of wind and solar powers. If the storage system is overdimensioned, it leads to an unnecessary elevation in the installation capacity cost as well as the operational cost. On the other hand, if the storage system is less than the required size, it will result in power outages, hence making the system less reliable. Therefore, there is a tradeoff between system reliability and costs, which can only be addressed by the development of efficient capacity estimation techniques for the BESS. Numerous research works have been carried out in this regard for optimal sizing of storage systems along with the generation units such as wind and solar PV plants [16–20]. The complementary nature of these resources is utilised for determining the optimal capacity of a BESS. However, there is a lot of room for novel research ideas in this field for minimising the operational costs and maximising profits.

Most recently, hybrid generation configurations involving wind and solar power sources have attracted much attention [21–23], recognised as an option of delivering power to remote locations. Complementary power production features of RE sources have contributed to the growth of hybrid generation systems [24]. It is a tedious task to integrate the un-controllable RE resource into an existing design of an electrical power grid [25–27]. For the overall domain of finding remedies for several technical issues in the RE field as discussed above, extensive studies and research are the need of the hour. These issues have utmost importance for the delivery of renewable power at an affordable cost such that the reliability and stability of the power grid are not affected adversely. This outlines the main goal of the proposed research work and makes it a fervent effort toward the contribution for RE technology progress.

In this paper, an attempt is being made to answer the intrinsic problems of RE sources through a hybrid wind–solar power system design. The hybrid wind–solar structure offers several basic advantages due to the complementary power profiles of both wind and solar. Since the continuous supply from these intermittent power sources is not guaranteed; a BESS is used to support the renewable power plants or as backups as mentioned earlier; however, the size of BESS is always a concern due to high cost. Therefore, the main contribution of this work is to present a strategy for joint planning and optimisation of the wind–solar mix for the hybrid power plant along with the optimal capacity of BESS to meet the load demand at the given location. Many recent research works can be found targeting the wind–solar complementarity assessment [10, 24] and optimal sizing of BESS separately [6, 15] but the simultaneous planning of a complete power system using both of these concepts is an innovative phenomenon that still has room for contribution. In summary, our research targets the following main points directly or indirectly:

- Renewable resource assessment for combined solar and wind.
- Optimal allocation of the renewable power mix.
- Optimal ESS.
- Cost optimisation.
- Reliability enhancement.
- Risk mitigation.

Another significant contribution of this work is the manner of optimisation problem formulation and algorithm development. The proposed formulation gives optimal results but at the same time it is simple, easy to understand, and implement, and takes into account the practical constraints about BESS. As a case study, the proposed technique was tested with actually observed datasets obtained from an Australian wind farm, Woolnorth in Tasmania, and solar PV data from University of Queensland (UQ) Solar St. Lucia campus which is the largest integrated PV installation in Brisbane, Australia.

The rest of this paper is structured as follows. Section 2 presents the problem description. The proposed methodology is demonstrated in Section 3. The datasets are described in Section 4. Section 5 summarises the main results along with discussion, followed by a conclusion in Section 6.

2 Problem description

As mentioned earlier, the overall theme of this research work is to propose an optimal design for renewable power generation systems, which is achieved by optimal resource allocation and optimal storage capacity. When solar and wind resources are allocated in appropriate proportions, it ensures that they are not overdimensioned. Similarly, the higher cost of ESSs is a serious issue for renewable power applications. Hence minimising the size of the BESS and optimising its operation via advanced optimisation and control mechanisms is considered crucial. In fact, these efforts reduce the initial capital cost and increase the lifetime of the installed renewable power plants and associated storage systems. Therefore, accurate storage sizing along with an optimal combination of renewable power resources, as proposed in this research, will be vital factors for the future economic feasibility of such plants that can potentially make the design more attractive for investors/developers.

Nowadays, stand-alone systems with solar and wind resources are receiving full attention over the globe at larger scale comparatively [28]. However, such plants cannot produce reliable

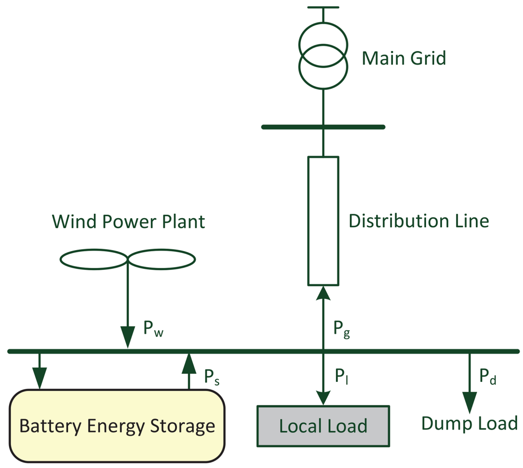

Fig. 1 *Stand-alone wind-storage system*

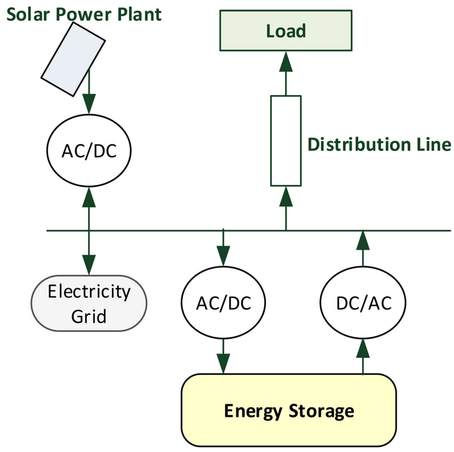

Fig. 2 *Stand-alone solar-storage system*

power independently owing to the seasonal characteristics of solar and wind power. For instance, the power generation from the stand-alone solar system is not available during non-sunny days. In the same manner, the power obtainable from a stand-alone wind system has significant fluctuations, and hence cannot meet constant load requirements. Additionally, there occur deviations in system frequency and power outages when the wind power integration is significant. To mitigate these issues, a BESS is attached to the system. For illustration purposes, stand-alone wind and solar systems employing energy storage are shown in Figs. 1 and 2, respectively.

However, the benefits of ESS come at a price, and the cost efficiency of hybrid renewable systems depends largely on the cost of storage system because the storage technologies are generally expensive. Therefore, the solution is to use hybrid RE systems and employ a common optimal BESS capacity, i.e. minimum energy storage requirements to supply the demand reliably at all times along with given RE resources. Now, a more complex optimisation problem is formulated with an objective to minimise the battery capacity along with an optimal combination of solar and wind generation mix. The optimisation scheme formulated in this manner is a high-dimensional non-convex mathematical problem and can be solved using mathematical tools such as quadratic programming (QP), dynamic programming, and so on.

The proposed work can be carried out in two sub-phases effectively: (i) design of solar and wind energy mix in optimal proportion and (ii) optimal design of BESS. In the hybrid solar–wind design phase, we can formulate an optimisation problem in order to find the optimal ratios of solar and wind sources at a certain remote location so as to deliver the required power demand. This can be done by specifying the objective of the optimisation problem for minimisations of power deviations between the desired power demand and combined solar–wind system power output. It is also required to satisfy certain physical system and cost

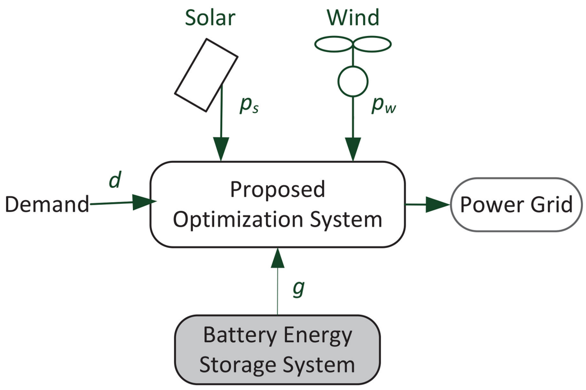

Fig. 3 *Proposed power system with hybrid wind–solar generation and BESS*

constraints during the operation of the hybrid RE plant. Finally, an overall optimisation completes the design.

3 Proposed methodology

As mentioned earlier, the primary focus of the proposed work is to design renewable power system based on solar–wind generation mix and BESS through adequate assessment and utilisation of the RE sources available in the given region. Thus, the first phase of the project is concerned with combined wind and solar resource assessment from selected sites. In the design phase of the proposed work, wind and solar energy resources will be combined in optimal ratios so as to minimise the demand-supply error. However, to completely meet the demand at all times, a BESS with optimal capacity will be attached to the hybrid RE system (see Fig. 3) so as to minimise the overall system costs.

3.1 Problem formulation

Let us define the hybrid generation using a function p_w for wind farm power output, with a ratio α to be optimised, and p_s with a ratio β for solar power output. Let d be the power demand at a certain geographical location, then such an ideal hybrid RE plant without storage can be defined as

$$d \cong \alpha p_w + \beta p_s \tag{1}$$

The objective function to be minimised is

$$\sum_{k=1}^{N} (d(k) - (\alpha p_w(k) + \beta p_s(k)))^2 \to \min_{\alpha,\,\beta} \tag{2}$$

The final time N should be chosen so that the time interval $[1, N]$ corresponds to a 1 year period. If c_w and c_s are the costs associated with wind and solar power plants, respectively, and c_h represents the maximum possible total cost of the hybrid RE system. Then, we can subject our optimisation problem to the following list of constraints:

$$\alpha c_w + \beta c_s \le c_h \tag{3}$$

$$\alpha > 0, \quad \beta > 0 \tag{4}$$

In (1), the formulation presented without energy storage, however, in most practical situations, a BESS is attached with such a hybrid RE system and finding out the optimal capacity of the BESS is also an important research problem. Hence, the problem statement can be redefined as a combination of three optimisation sub-problems: (i) optimal BESS power flow for a given capacity C, (ii) optimal allocation of wind (α) and solar (β) generation mix for a selected BESS, and (iii) overall optimisation with optimal BESS capacity.

3.2 Optimal BESS power flow

In this first part of optimisation, our goal is to obtain an optimal battery power flow g for a given BESS capacity C. The objective function aims at matching the supply with demand in the presence of cost constraints as follows:

$$J_D = (d - (p_t - g))^T (d - (p_t - g)) \tag{5}$$

where p_t is the total net generation of the hybrid wind–solar system. The description of the optimisation sub-problem is given by the following procedure.

Let $C > 0$ denote the total battery capacity, $z(k)$ as the available energy in the battery at a time instant k, $r_c > 0$ as the maximum rate of charge, and $r_d > 0$ as the maximum rate of discharge. Then, any current state of the battery should satisfy the following constraint:

$$-r_d \le z(k+1) - z(k) \le r_c \quad \forall k \ge 0. \tag{6}$$

Also, if $0 < \alpha_m < \alpha_M < 1$ are the given limits. Then, in order to prolong the lifetime of a battery that consequently reduces its cost, the following constraint about BESS capacity limits should be satisfied:

$$\alpha_m C \le z(k) \le \alpha_M C \quad \forall k \ge 0. \tag{7}$$

where α_m is the lower limit of battery discharge, whereas α_M is the upper limit of battery charging for a chosen operational band. For example, 30–70% band with lower and upper bounds as ($\alpha_m = 0.3$, $\alpha_M = 0.7$). Note that the selection of particular operational band is dependent on the type of battery and/or significance. For illustration, the significance of 30–70% operational band for lithium-ion batteries is demonstrated in [29].

For the sake of compatibility, we scale the generated power with the demand. First, considering the actual power p of the hybrid wind–solar power plant

$$p = p_w + p_s$$

Then, p can be normalised according to the given demand d as follows:

$$d_s = \text{mean}(d)$$
$$p_s = \text{mean}(p)$$
$$\kappa = \frac{d_s}{p_s}$$

After applying this normalisation, the scaled renewable power output of the hybrid RE plant can be given as

$$\hat{p}_t = \kappa p \tag{8}$$

The power difference vector representing the supply–demand mismatch can be defined as

$$\boldsymbol{v} = d - \hat{p}_t$$

The optimal battery power flow in both directions, i.e. charge or discharge, can be determined using an innovative method proposed here based on power difference thresholds D_1 and D_2, where $D_1 < D_2$. According to this method, the battery charge/discharge function g is decided on the basis of the power difference vector and their thresholds as follows:

$$g(k) = \begin{cases} 0 & \text{if } D_1 < v(k) < D_2 \\ \min\{r_c, \alpha_M C - z(k)\} & \text{if } v(k) \le D_1 \\ -\min\{r_d, z(k) - \alpha_m C\} & \text{if } v(k) \ge D_2 \end{cases}$$

```
function g^opt(C) = OBPF(N, z(1), d, p̂_t, v, C)
Initialization: N_s ← 50, J_min ← ∞
D_M ← max{v}
D_m ← min{v}
δ_v ← (D_M − D_m)/N_s
for j_1 = 1 : N_s − 1 do
    D_1 ← D_m + (j_1 − 1)δ_v
    for j_2 = 1 : N_s − j_1 do
        D_2 ← D_1 + j_2 δ_v
        for k = 1 : N do
            if D_1 < v(k) < D_2 then
                g(k) ← 0
            else if v(k) ≤ D_1 then
                g(k) ← min{r_c, α_M C − z(k)}
            else if v(k) ≥ D_2 then
                g(k) ← − min{r_d, z(k) − α_m C}
            end if
            z(k+1) ← z(k) + g(k)
        end for
        J_D ← (d − (p̂_t − g))^T (d − (p̂_t − g))
        if J_D < J_min then
            D_1^opt ← D_1
            D_2^opt ← D_2
            g^opt(C) ← g
            J_min ← J_D
        end if
    end for
end for
end function
```

Fig. 4 *Algorithm 1: optimal battery power flow (OBPF)*

Now, the optimal set of thresholds $\left(D_1^{\rm opt},\ D_2^{\rm opt}\right)$ needs to be determined, in accordance with the cost function $J_{\rm D}$ in (5). To achieve this, Algorithm 1 (see Fig. 4) is proposed in this paper which leads to an optimal battery power flow $g^{\rm opt}(C)$ for a given BESS capacity. Here, we consider $p_{\rm t} = \hat{p}_{\rm t}$ and $x(k)$ varies according to the battery dynamic model .

3.3 Optimal combination of renewable power plants

The goal of this part of optimisation is to allocate the wind (α) and solar (β) generation mix optimally so that the required power demand d is met with minimum cost. It is important to note that we have already determined the optimal power flow from a BESS $g^{\rm opt}(C)$ as described in Section 3.2.

To convert the problem in standard quadratic form, few vectors can be defined as

$$\boldsymbol{\phi}(k) = \begin{bmatrix} p_{\rm w}(k) \\ p_{\rm s}(k) \end{bmatrix}, \quad \boldsymbol{u} = \begin{bmatrix} \alpha \\ \beta \end{bmatrix}$$

Thus, the optimal problem to be solved can be stated as

$$\begin{aligned} u^{\rm opt}(C) \triangleq \min_u \quad & \left\{ J_{\alpha\beta} = \sum_{k=1}^{N} \left(d(k) - g^{\rm opt}(k) - \phi(k)^{\rm T} u\right)^2 \right\} \\ & {\rm s.t.}\ \alpha c_{\rm w} + \beta c_{\rm s} \le c_{\rm h} - c_{\rm B} \\ & \alpha > 0,\ \beta > 0 \end{aligned} \tag{9}$$

where $c_{\rm h}$ is the maximum projected cost of the hybrid wind–solar system as mentioned earlier in (3), whereas $c_{\rm B}$ is the cost of the associated BESS, now included in the formulation.

Generally, the cost function in standard quadratic form can be written as

$$J_{\alpha\beta} = u^{\rm T} H u + 2 f^{\rm T} u + \gamma \tag{10}$$

where H, f, and γ can easily be found by converting objective function in (9) into standard quadratic form (10). To do that we explain the procedure very briefly as follows: note that (9) can also be written for a single instance as:

$$\begin{aligned} & (d(k) - g^{\rm opt} - \alpha p_{\rm w}(k) - \beta p_{\rm s}(k))^2 \\ & = (d(k) - g^{\rm opt} - \phi(k)^{\rm T} u(k))^2 \\ & = (d(k) - g^{\rm opt} - \phi(k)^{\rm T} u(k))^{\rm T} (d(k) - g^{\rm opt} - \phi(k)^{\rm T} u(k)) \\ & = u(k)^{\rm T} \phi(k) \phi(k)^{\rm T} u(k) - 2(d(k) - g^{\rm opt}) \phi(k)^{\rm T} u(k) \\ & \quad + (d(k) - g^{\rm opt})^2 \end{aligned}$$

Therefore, by comparison H, f, and γ can be extracted as

$$H = \sum_{k=1}^{N} \phi(k)\, \phi(k)^{\rm T} \in \mathbb{R}^{2 \times 2}$$

$$f = \sum_{k=1}^{N} \left(g^{\rm opt}(k) - d(k)\right) \phi(k)^{\rm T} \in \mathbb{R}^{1 \times 2}$$

$$\gamma = \sum_{k=1}^{N} \left(d(k) - g^{\rm opt}(k)\right)^2 \in \mathbb{R}$$

Note that here γ does not depend on u. Finally, standard QP algorithms can be used to solve the following quadratic optimal problem with inequality constraints using MATLAB software:

$$\begin{aligned} u^{\rm opt}(C) \triangleq & \min_u \left\{ \bar{J}_{\alpha\beta} = u^{\rm T} H u + 2 f^{\rm T} u \right\} \\ & {\rm s.t.} \quad Au \le b \end{aligned} \tag{11}$$

where

$$A = \begin{bmatrix} c_{\rm w} & c_{\rm s} \\ -1 & 0 \\ 0 & -1 \end{bmatrix}, \quad b = \begin{bmatrix} c_{\rm h} - c_{\rm B} \\ 0 \\ 0 \end{bmatrix} \tag{12}$$

3.4 Overall optimisation

Finally, one can combine both optimisation problems, Sections 3.2 and 3.3, to obtain an optimal combination of renewable plants and consequently for the optimal capacity of the BESS. It can be achieved by invoking the two mentioned optimisation problems for a range of BESS capacities. This is presented in the combined Algorithm 2 (see Fig. 5), which yields the overall design of hybrid wind–solar system optimal values, i.e. the optimal ratio of combining renewable power plants $\alpha^{\rm opt}$, $\beta^{\rm opt}$ along with an optimal BESS capacity $C^{\rm opt}$.

Furthermore, we can determine the total energy contribution from the BESS, over the entire period of optimisation, with optimal capacity $c^{\rm opt}$ based on its optimal power flow, i.e.

$$E = \int \left(g^{\rm opt}(C)\right)^2$$

where $g^{\rm opt}(C)$ is obtained as explained in Section 3.2. Similarly, total energy contribution from renewable power resources over the given period of optimisation can be determined as

$$E_{\rm ren} = \sum_{k=1}^{N} (d(k) - \phi(k)^{\rm T} \boldsymbol{u})^2 - E \tag{13}$$

where $\boldsymbol{u}$ is the vector of parameters α and β, as explained in Section 3.3 obviously subjected to the constraints as in (9) .

4 Databases

To test the proposed strategy by simulations, actually observed datasets for wind, solar, and power demand are considered. Wind

function $[\alpha^{\text{opt}}\ \beta^{\text{opt}}\ C^{\text{opt}}]$ = **ORPC**$(N,\ N_c,\ x(1),\ d,\ \hat{p}_t,\ v,\ c_W, c_S, \hat{C})$

Initialization: $J_{\min} \leftarrow \infty$

$\vec{C} \leftarrow [C(1), \ldots, C(N_c)]$,

$\vec{c_B} \leftarrow [c_B(1), \ldots, c_B(N_c)]$

for $k = 1 : N_c$ **do**

  $g \leftarrow$ **OBPF**$(N, z(1), d, \hat{p}_t, v, C(k))$

  $Q \leftarrow [\phi(1), \ldots \phi(N)]^T$

  $H \leftarrow Q^T Q$

  $f \leftarrow -Q^T(d - g)$

  $u \leftarrow$ **QP**$(H, f, c_W, c_S, \hat{C}, c_B(k))$

  $\bar{J}_{\alpha\beta} \leftarrow u^T H u + 2 f^T u$

  if $\bar{J}_{\alpha\beta} < J_{\min}$ **then**

    $\alpha^{\text{opt}} \leftarrow u(1)$

    $\beta^{\text{opt}} \leftarrow u(2)$

    $C^{\text{opt}} \leftarrow C(k)$

    $J_{\min} \leftarrow \bar{J}_{\alpha\beta}$

  end if

end for

end function

Fig. 5 *Algorithm 2: optimal renewable plants combination (ORPC)*

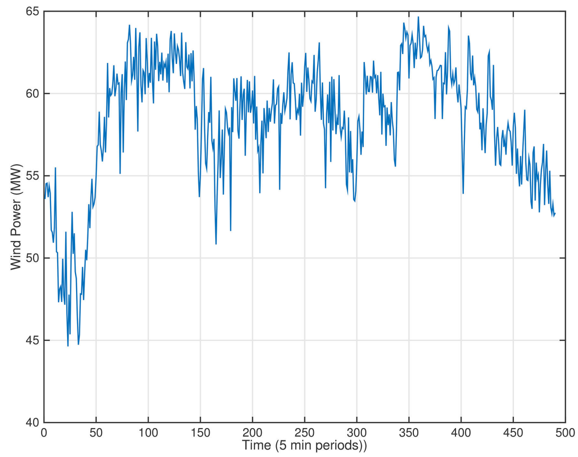

Fig. 6 *Actual wind power profile*

and solar power data are obtained from a wind farm at Roaring 40s Woolnorth, Tasmania and UQ Solar at the University of Queensland, Australia, respectively. Australian electricity market operator is chosen for load/demand data acquisition.

5 Results and discussion

The proposed strategy has been tested using a real-world case study. The actually recorded wind power profile from the selected location is shown in Fig. 6 for 500 samples for the sake of clarity in presentation. Similarly, the solar power profile from the selected solar PV farm is shown in Fig. 7.

For case study 1, the model performance is evaluated in terms of how closely it tracks the actual power demand, and the result is shown in Fig. 8. It is important to note that the hybrid wind and solar power profile are scaled to match the given demand as explained in (8). Thus, Fig. 8 depicts how well the hybrid wind–solar power output is able to supply the demand profile over the given time period. This includes time instants where we have an excess of produced power and also where the generation fails to supply the demand and the deficiency should be compensated by the BESS. Similarly, Fig. 9 shows the model performance to track the actual power demand for the Australian state of Victoria (VIC).

The optimised model parameters for both NSW and VIC are summarised in Table 1, i.e. number of solar PV plants, number of wind farms, and BESS capacity in megawatt hour. These are the outputs of the optimisation Algorithm 2 (Fig. 5) found on the basis of overall system cost minimisation including the cost of RE plant and BESS. This optimisation criterion is evident from the objective

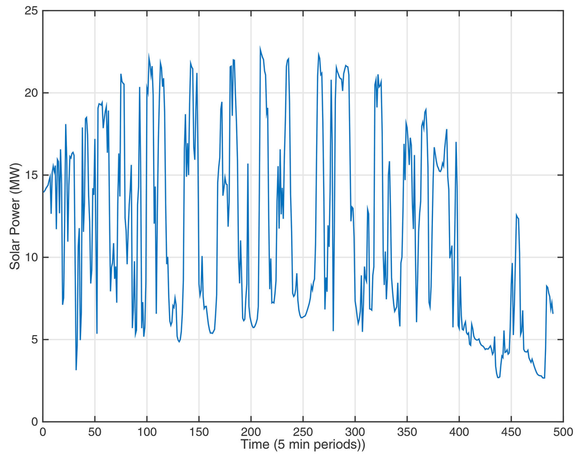

Fig. 7 *Actual solar power profile*

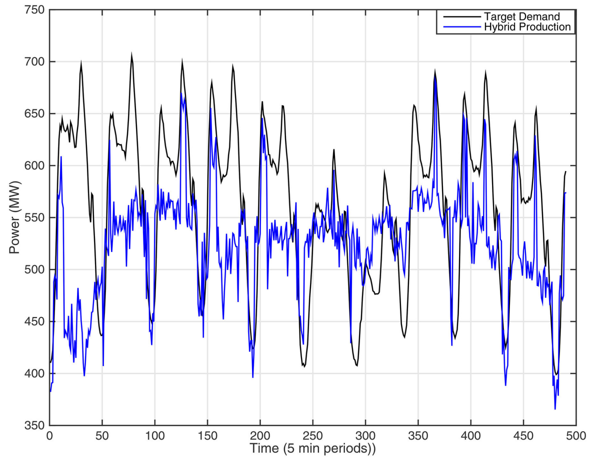

Fig. 8 *Model's tracking performance for the state of NSW*

function and constraints in (9) that is shown after conversion into a standard QP problem in (11) and (12). Finally, we have compared the demand tracking performance of the model (i) for renewable power production only, i.e. without any energy storage and (ii) using the storage in order to show the power contribution from the BESS. The normalised error for both cases is shown in Figs. 10 and 11. Furthermore, it is extremely important to mention that obviously the proposed final design is not an actual one for the respective states, rather it is an illustration of the proposed design method, which can be used to determine the actual optimal design parameters for any location with actual or accurate values of all system parameters.

The total investment cost c_h and BESS cost c_B is an important design parameter for the proposed wind–solar hybrid plant with the BESS. In fact, the total cost c_h becomes a limiting factor in the optimal BESS capacity estimation owing to the high BESS cost which covers the major portion of c_h. For example, it can be seen from Table 1 that the design of a hybrid system for NSW and VIC have different optimal parameters because of the high value of demand and other associated parameters. The unit cost estimates of wind c_w and solar plants can be obtained from the web [30, 31]. The upper limit c_h of the proposed hybrid system is adjusted starting with a reasonable initial guess, and hit and trial method for better matching renewable power generation with demand of optimal BESS. Finally, we propose nine wind farms and three solar PV plants to fulfil the given power demand for NSW supported by BESS, and eight wind farms and ten solar PV plants along with BESS to meet the given demand for VIC. It is important to overview the cost details of different BESSs with a variety of power and energy ratings and types over the past few years (see, e.g. [32–35] and references therein).

The proposed scheme can bring many benefits from the perspective of cost-effective hybrid power system planning. The

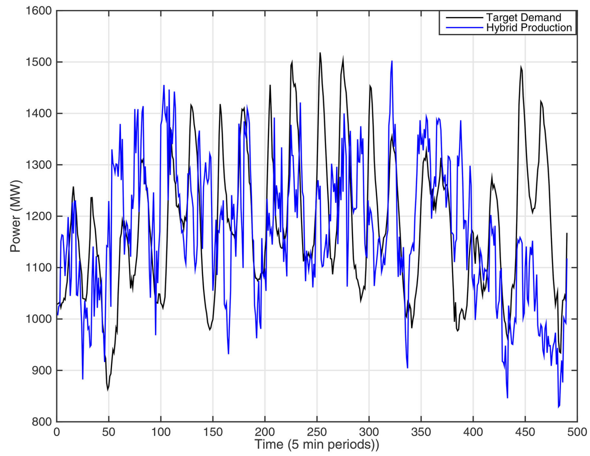

Fig. 9 *Model's tracking performance for the state of VIC*

Table 1 Design parameters

State	Wind (α^{opt})	Solar (β^{opt})	Storage (C^{opt}, MWh)
NSW	9	3	86
VIC	8	10	51

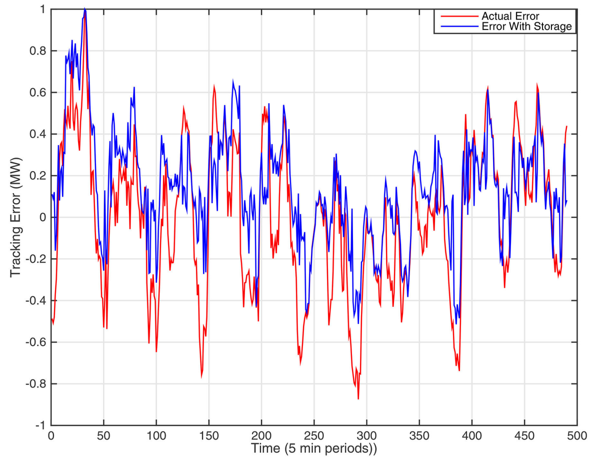

Fig. 10 *Normalised error of the model with and without BESS for NSW*

scheme aims at the optimal allocation of the wind–solar mix, which is ensured through the constraint in (9) that the sum of both power plant costs along with their respective mix ratios and the BESS cost as well should remain less than a projected investment cost. Another important feature of the proposed framework is optimal energy storage, which is maintained from two perspectives, calculating the optimal battery power flow and minimising the BESS capacity according to the cost. This is achieved by modelling the various practical BESS constraints including maximum and minimum rates and limits of battery charge/discharge etc. and using the concept of power difference thresholds.

The basis of the optimisation problem formulation for wind–solar optimal allocation as well as BESS capacity optimisation is considered as the cost of these entities. This leads to cost optimisation which is always a vital consideration for the power industry. In addition, the reliability of the proposed hybrid generation is maintained by the introduction of BESS and the set-up of the optimisation problem through (2) and (9), which keeps the generation–demand matching even in times of power deficit using the stored energy from the BESS. The function OBPF [Algorithm 1 (Fig. 4)] also ensures that energy is supplied from the BESS in times of need, whereas Algorithm 2 (Fig. 5) tries to do so with optimal BESS capacity. Hence, the reliability of the system is ensured at all times and the risk of system failure is mitigated using the proposed system optimisation and optimal sizes obtained as a result.

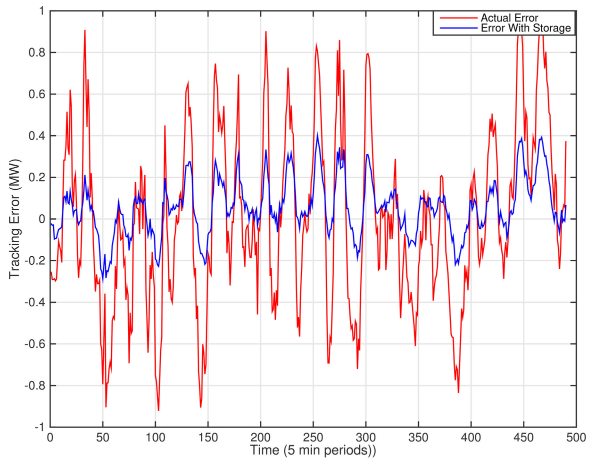

Fig. 11 *Normalised error of the model with and without BESS for VIC*

Moreover, the proposed scheme should be based on the wind and solar power potentials available at the same location and time period, in principle. However, the results are presented based on the data from two different locations in Australia because of the unavailability of the required data in synchronisation. It was observed that the proposed methodology gives effective outcome even in case of two distant geographical locations but a consistent data from the same geographical location is expected to produce even better results as it will actually benefit from complementary profiles of wind and solar RE sources.

6 Conclusion

In this paper, a hybrid structure of a renewable power plant containing wind and solar generation mix coupled with an optimal BESS capacity has been proposed. This design is able to optimally match load demand at a particular region with the optimal renewable resource allocation at minimum cost. The case studies are based on the actual power demand from two different states in Australia using data from two distinct geographical locations. The designed power system with hybrid RE resources not only offers demand matching but also ensures optimal utilisation of resources. An innovative method to determine the optimal power flow for a given BESS capacity in both charge/discharge actions is proposed and shown to be quite effective through simulation results. The concept of complementary characteristics of solar and wind generation is well-utilised to allocate both these resources in optimal ratios for the given case studies. Keeping in view the high BESS cost, its optimal capacity is also determined along with the associated hybrid wind–solar system as an overall optimum solution. The practical constraints of the BESS, supply–demand matching, and cost are taken care of in all simulations. The results obtained through two case studies at different sites prove the effectiveness of the proposed strategy.

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