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A Weather Aided State Estimator for Power Systems with Integrated Variable Energy Resources

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***Abstract*—In recent years, the penetration of renewable energy sources has increased, thus coupling the power grid to the variability of weather patterns. These variable energy resources (VERs) have the potential to raise the vulnerability of the power grid after sudden changes of weather. Given these new power grid behaviors, the goal becomes to provide the operator with a greater level of situational awareness. This work proposes a methodology to enhance the core of the Energy Management system – the state estimator. Traditional state estimation (SE) is combined with weather forecast data to provide the operator with an understanding of the system behavior a step into the future. This “Weather-Aided State Estimator” can enhance the system operator’s reaction to weather events with advanced notice and forewarning; enabling greater reliability of power grids with a high penetration of VERs. The paper outlines the methodology to implement the WASE along with results to illustrate the information which can be provided to the operator.**

I. Introduction

State Estimation (SE) is a key tool in any Energy Management System (EMS). It is an optimization algorithm which estimates the voltages (V) and phase angles (θ) at every bus in a given power grid for a given set of measurements Z. Together, the voltages and phase angles are defined as the system state. Monitoring its variation is essential to ensuring the reliable operation of the power grid. The measurements used for SE include active power injection, reactive power injection, active power flow, reactive power flow, phase angle and voltage measurements [1].

Extensive years of research on SE have successfully implemented algorithms which cover issues such as observability [2], [3], bad data analysis [4], computational time and complexity [5]. Recent developments in dynamic state estimation (DSE) include load forecasts, which are based on a priori information to build the time varying model of the power systems [6]. A number of reviews on the subject have been produced in the literature [7]–[9].

In the Weather Aided State Estimator (WASE), short term weather forecast data is used to identify different weather phenomena and perform SE. The WASE can help create early warning systems which improve the situational awareness of the operators. This provides the information necessary to take appropriate action before the weather phenomena affects the power grid operation. Such an algorithm runs in parallel to a regular SE and alerts the operator of the upcoming weather events. In this paper, a methodology is developed to use forecasted weather information to enhance the operator’s understanding of the power system conditions as variable energy resources inject power that is vulnerable to sudden weather changes.

The remainder of this paper develops over four sections. The motivation is explained in Section II followed by the methodology to implement WASE in Section III. The simulation of the methodology is provided in Section V and the conclusion is stated in Section VI.

II. Motivation

The share of renewable energy in the generation mix is set to increase over the coming years to meet the growing energy demand and at the same time address issues of climate change and carbon emissions [10]. Currently, power grids are subjected to fluctuations in load and in the future will be affected by fluctuations in generation due to the increase in the presence of VER [11]. The higher penetration of VER in power grids increases the vulnerability of these systems to weather phenomena. For example, the now well-studied ERCOT event in 2008 showed how wind generation can create a ramp event in which 90% of operating reserves had to be deployed. Similarly, cumulus clouds have been known to cause significant variability in solar PV generation. Even demand side resources are affected by weather as HVAC systems respond to passing storm fronts. Within the middle east, dust storms have the potential to impact solar generation. In order to maintain the reliability of the power grid operation, it is necessary to improve the monitoring and control systems [12] so as to capture the effect of the weather on the power grid.

The WASE aims to aid the operator with the prediction of the system states to ensure that the three main operations listed below can be improved in the presence of fluctuations introduced by the VERs. The main concerns of the power system operator are as follows:

- Balance generation and load which is performed by ensuring frequency stability.
- Maintain voltage stability.
- Maintain thermal limits which includes monitoring the power flow through the tie lines.

The WASE presented in this paper highlights how each of the above-listed operator actions can be enhanced to meet the challenges posed by the presence of VERs. Fig. 1 shows the block diagram of the integration of WASE into the current structure used in the EMS.

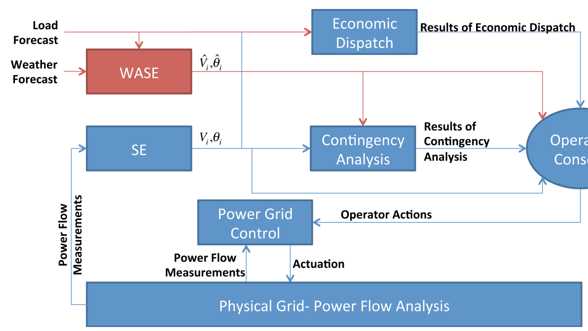

Fig. 1. Integration of the Weather Aided State Estimator

The weather-aided state estimator gains further importance when taken in the context of the layers of power system control; be it primary, secondary, or tertiary. Primary control – or the real-time automatic feedback control of the power system – is based upon local measurements of power system voltages and currents. While it does have the ability to respond to weather variability, the amount of control capability is ultimately limited [13]. In contrast, the tertiary control provided by the market layer does take into consideration weather and load forecasts, but the results from the economic dispatch are refreshed at a much slower rate than desired. The time scale of this operation ranges from 5min to 1hour. The low frequency of operation of the market layer is not necessarily able to capture sudden events in the weather and thus does not improve the operator's situational awareness. Moreover, the markets perform a security constrained economic dispatch [14] which is merely an approximation of the power system states.

Several surveys and studies have highlighted the need to include weather forecasts in the EMS to equip the operators to manage weather events which can affect the power grids. In [15], the authors highlight the need for improving the information available on renewable energy generation to enhance the operation of the smart grids of tomorrow. The successful integration of VERs is supported by the use of operating reserves, the management of which can be improved with the aid of forecasts. In [16], the need to develop special operating procedures to perform balancing when dealing with VERs is discussed. The recommendations provided in [17] to update power system monitoring include improvements in the operating procedures to handle the events which arise in the power grid due to weather phenomena. The inclusion of forecasts and relaying the information to the operator is highlighted as an important step to enhance situational awareness which can improve the operator's reaction to a problem. The literature survey conducted in [16], [17] and [15] have concluded that there is a need to enhance the operating procedures by providing forecasts yet to be developed.

The WASE proposed in this paper aims to combine the advantages of short term forecasts with power flow analysis. The results of the WASE can be used directly to aid the operator in making decisions when a weather phenomena occurs. The WASE is an online tool which generates forecasted state values based on forecasted weather information.

III. Methodology

In this section, the methodology for implementing the WASE is discussed. The high level objective of the WASE is to provide foresight into the power system reliability by using a steady state model. The WASE methodology provided

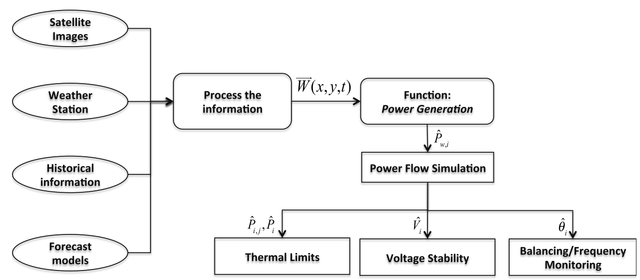

Fig. 2. Block diagram of proposed WASE methodology

in Fig. 2 can be divided into five separate stages:

1) Collect weather data
2) Process weather information
3) Execute power generation/consumption function
4) Perform power flow analysis
5) Process the results of the power flow analysis

The function of each stage and how it eventually aids the operator's situational awareness is elaborated in the remainder of this section.

A. Collect weather data

The input weather information can be collected from several sources. Developments in the fields of communication, weather forecasting and meteorological sciences have resulted in vast amounts of data which can be utilized by the WASE. The average time taken by the operator to react to any event is 15 min, thus such a look-ahead window should be achieved by the WASE to benefit operators. Therefore, the forecast models are required to be short-term forecasts of the order of 15-30 minutes [18]. Furtheremore, forecasts must be able to capture ramp events and variability [19]; both of which can cause significant shifts in the VER power generation. The weather station information can also be combined with historical data to understand the evolution of the weather over a given period of time. Finally, satellite imaging or Geographical Information Systems(GIS) can be used to enhance the weather data collection techniques [20]. The performance of the WASE is dependent on the availability and accuracy of the weather data, which is bound to improve with the further developments in communication and forecast models.

B. Process weather information

The data collected from the sources discussed in the previous section should be compiled to suit the power system analysis. The data is used to build a time-varying spatial map for a given time frame of the weather variables $W_k(x,y)$. The map provides the weather data W at time k for the geographical locations given by coordinates (x,y). The power system buses should have coordinates which correspond to their physical location and can be used to identify the weather variable at each bus. Therefore, the geographical mapping of the grid is an essential prerequisite for the implementation of this scheme.

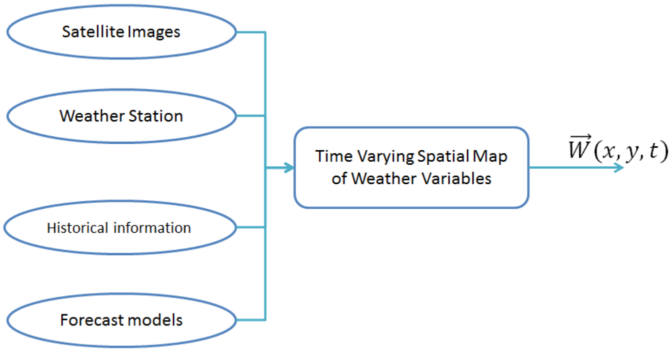

Fig. 3. Collection of weather data

C. Execute power generation/consumption function

Once the time-varying spatial map of the weather variable is obtained for a given period into the future, it is used to forecast the power injection at the buses affected by the weather variables. The VER can include wind farms with the power function directly proportional to the wind speed, solar PV farms which have a power function directly proportional to the solar irradiance. Similarly, buildings which represent the load buses can have power consumption functions which have a direct correlation to temperature and humidity as well. Due to the heterogeneity of such building models such power functions do not exist, but a future development of such models can also be incorporated to the WASE. This step connects the weather data to the power system by generating the forecasted power generation profile. The output from the power generation function is used in the following step for power flow analysis.

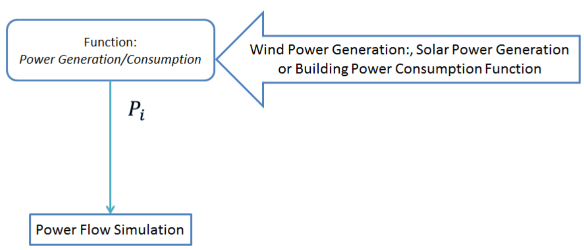

Fig. 4. The power function which can be adopted to generate the power injection profile

D. Power flow analysis

Weather variability directly causes variability in these power injection function which subsequently ripple through the grid. A power flow analysis is performed to measure these effects. Equations 1 and 2 are solved to obtain the full list of the system states for each set of forecasted values.

$$P_i = |V_i| \sum_{j=0}^{n} |V_j|(G_{ij}cos(\theta_i - \theta_j) + B_{ij}sin(\theta_i - \theta_j)) \quad (1)$$

$$Q_i = |V_i| \sum_{j=0}^{n} |V_j|(G_{ij}sin(\theta_i - \theta_j) - B_{ij}cos(\theta_i - \theta_j)) \quad (2)$$

The results of the power flow analysis provides the values for the system states $\hat{x}(k)$, corresponding to each instant k into the future. The power flow analysis performed using the steady state equations can also be replaced with a dynamic model of the power grid.

E. Process the results of the Power Flow Analysis

The power flow analysis provides more information than just the state vector. The state vector can be used to calculate the power flow between the buses using Equations 3 and 4.

$$P_{ij} = |V_i||V_j|(G_{ij}cos(\theta_i - \theta_j) + B_{ij}sin(\theta_i - \theta_j)) - Gi|V_i|^2 \quad (3)$$

$$Q_{ij} = |V_i||V_j|(G_{ij}sin(\theta_i - \theta_j) - B_{ij}cos(\theta_i - \theta_j)) + Bi|V_i|^2 \quad (4)$$

The various results obtained from the power flow analysis are able to aid the three main responsibilities of the operator described in Section II. The system states provide the voltage and phase angles which are used for monitoring both voltage stability as well as frequency stability. The power generation and the power consumption information provided by the power injection values along with the Area Control Error (ACE) are calculated and used to ensure balancing of the load and generation. The thermal limits are monitored with the help of the calculated power flow values. With the help of the information obtained from this step, the operator is able to better understand how the system will behave in the future when subjected to a change in the weather. The greater awareness of the system parameters and their evolution improves operators' reactions to weather events.

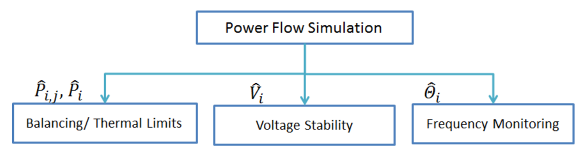

Fig. 5. Processing of the powerflow results

IV. Integration of Weather Information with Power System

The meteorological models distinguish between areas of constant weather variables. For example, isobars delimit wind speeds. Similar approaches can be done for the other VERs. Therefore, it is necessary to model the evolution of these lines of constant temperature, solar radiation, and wind speed to develop the varying weather map. In this section, the model of a wind speed map is explained using the concept of a moving isobar.

Consider an arbitrary scalar field P which represents the air pressure. $\vec{W} = \nabla P$ is a vector field that represents air speed/wind speed.

$$\vec{W}(x, y) = W_x(x, y)\hat{i} + W_y(x, y)\hat{j} \quad (5)$$

The lines of equal wind speed are the same as the isobars, which are perpendicular to the motion of wind. The isobars are described by P(x,y)= c. Let the wind speed on one side of the isobar be $\vec{A}_1$ and the wind speed on the other side of the isobar be $\vec{A}_0$. The isobar can be represented as a parametric equation in u:

$$R(u) = R_x(u)\hat{i} + R_y(u)\hat{j} \quad (6)$$

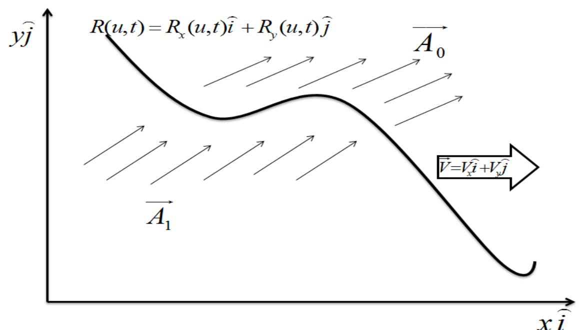

Fig. 6. Graphical representation of the WASE weather modeliing

If the isobar R(u,t) is moving with a velocity $\vec{V} = V_x\hat{i} + V_y\hat{j}$, the evolution of R(u,t) over a given period can be postulated as follows:

$$\vec{R}(u,t) = [R_x(u) + V_x t]\hat{i} + [R_y(u) + V_y t]\hat{j} \qquad (7)$$

The wind speed at a point (x,y) is also a function of time and it is represented as:

$$\vec{W}(x,y,t) = W_x(x,y,t)\hat{i} + W_y(x,y,t)\hat{j} \qquad (8)$$

The vector $\vec{W}(x,y,t)$ is updated with respect to $\vec{R}(u,t)$.

$$W_x(x,y,t) = \begin{cases} A_{1x} & \text{if x} < R_x(u,t) \\ A_{0x} & \text{if x} > R_x(u,t) \end{cases} \qquad (9)$$

$$W_y(x,y,t) = \begin{cases} A_{1y} & \text{if y} < R_y(u,t) \\ A_{0y} & \text{if y} > R_y(u,t) \end{cases} \qquad (10)$$

The energy from the wind speed $\vec{W}(x,y,t)$ which is harnessed by the turbine along the direction $\hat{s} = s_x\hat{i} + s_y\hat{j}$ is given by $\vec{W}_e(t) = \hat{s} \cdot W(\vec{x,y},t)$.

The IEEE 14 bus system [13] is used as the test case. In this paper, the VER adopted is a wind generator with a power generation function given by Equation 11 and the simulation is performed within a Matlab environment.

$$P_i = \frac{1}{2} \times \mu A v^3 \times C_P \qquad (11)$$

Where $C_P = 0.59$ is the coefficient of performance for the turbine which considers the efficiency and the turbine coefficient together. The area of the turbine A is set to 3848 m^2 and μ is the density of air is 1.2 kg/m^3 .

V. Results

Bus 2 in the IEEE 14 bus system is a generator bus and is substituted with the wind turbine. The wind data is forecasted and assumed to be collected from the sources which are mentioned in Section III. In this paper, a moving wind front along the horizontal direction is modeled. The wind farm is provided with coordinates ($x_{turbine}$,$y_{turbine}$). The wind speed corresponding to the point $\vec{W}_e$($x_{turbine}$,$y_{turbine}$,t) is used to calculate the generated power P_i.

The steady state power flow analysis is performed by MATPOWER within the Matlab environment [21]. The change in the wind speed over the geographical area of the grid is reflected in the power injection at Bus 2. The predicted power injection profile results in a spike in the power injection and the power flow analysis is performed for the time frame in the future.

The time frame of the predicted power generation profile is 2 min. The predicted power generation profile shown in Fig. 7 is used as an input at Bus 2 of the IEEE 14 bus system. The power flow analysis performed for the forecasted

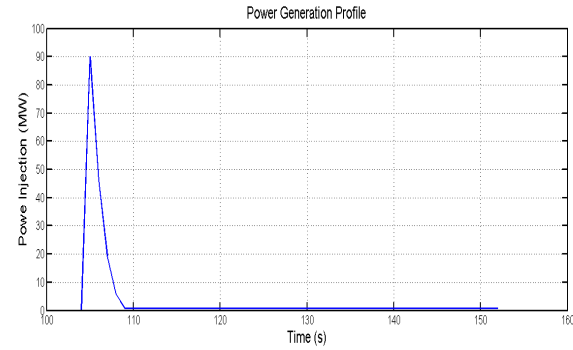

Fig. 7. Forecasted power generation profile

power generation and the results are highlighted to understand the behavior of the system when subjected to changing wind speeds. In Table I, the maximum and minimum values of the voltage and phase angle for the time frame can be observed. This allows the operator to maintain the voltage stability and frequency stability. Also the generator parameters [13] can be extracted and provided to the operators as shown in Table II, which can aid in making decisions related to balancing. The generator parameters provide the maximum active power, and maximum and minimum reactive power of the generators.

TABLE I. Collection of Voltage and Phase Angles // from the Power Flow Analysis

Bus	V_{max} (pu)	V_{min} (pu)	θ_{max}(deg)	θ_{min}(deg)	θ_{max}(deg)
1	1.06	1.06	0	0	0
2	1.05	1.05	-3.53	-6.16	2.63
3	1.01	1.01	-11.42	-13.77	2.35
4	1.02	1.02	-9.16	-11.24	2.08
5	1.02	1.02	-7.72	-9.62	1.90
6	1.07	1.07	-13.14	-15.09	1.96
7	1.06	1.06	-12.22	-14.28	2.05
8	1.09	1.09	-12.22	-14.28	2.05
9	1.06	1.06	-13.81	-15.85	2.04
10	1.05	1.05	-13.98	-16.00	2.02
11	1.06	1.06	-13.69	-15.68	1.99
12	1.06	1.06	-13.99	-15.95	1.96
13	1.05	1.05	-14.07	-16.03	1.97
14	1.04	1.04	-14.92	-16.93	2.01

TABLE II. Collection of Generator Parameters from the Power Flow Analysis

Bus	P_G (MW)	Q_{Gmax}(MVARS)	Q_{Gmin}(MVARS)
1	274.5	-4.95	-24.92
2	90.18	59.81	24.42
3	0	25.16	25.00
6	0	12.78	12.71
8	0	17.65	17.59

The power flow analysis results provides more information than necessary. “Data overload” can be a risk. Operators require concise information about the essential parameters to make clear and quick decisions. The development of Graphical User Interface (GUI) for conveying the critical information to

Power Flow				
Critical Lines	1-2	2-5	4-7	12-13
Maximum(p.u)	1.92	0.45	0.28	0.02
Time Instant	1	6	6	1

Voltage				
Critical Buses	2	4	5	7
Maximum(p.u)	1.05	1.02	1.02	1.06

Phase Angle				
Critical Buses	2	4	5	7
Max	-3.53	-9.16	-7.72	-12.22
Min	-6.16	-11.24	-9.62	-14.28

Area Control Error (MW)										
Time Instant	1	2	3	4	5	6	7	8	9	10
ACE	42.47	42.47	42.47	42.47	42.47	-52.53	-6.51	21.71	36.38	41.70

Fig. 8. List of essential parameters of critical buses and tie lines

the operators is a crucial part of the the EMS [22] [23]. A simple illustration of the necessary information is provided in Fig. 8. Fig. 8 provides the information about the critical components of the power system, it includes the power flow between critical tie lines in power per unit, the voltage per unit and phase angle at the critical buses in degrees and also the area control error (MW) is provided over the future. The time instant in the future, when the event will occur is also provided. If the P_{max} for the line between the buses 1 - 2 is calculated as 1.8p.u, from the Fig. 8 it can be observed that there is a violation of the thermal limit and the operator can take the necessary action to prevent the same. Similar GUIs and visualization tools can be developed to exploit the WASE and improve the operator's understanding of the power grid when subjected to various weather conditions [24] .

VI. Conclusion

The work in this paper proposes a methodology to enhance SE which is a key source of data for decision making in the EMS. The proposed addition of weather data to enhance the SE is able to improve the operator's situational awareness in power systems with high VER penetration. The modeling approach to represent a time varying map of wind speed can be expanded to represent other sources utilized by VERs. The results simulated a spike in the power injection and displayed the several parameters which are obtained as part of the power flow analysis. The WASE supported by a strong GUI can relay the evolution of critical information in the future to support the operator in making clear and quick decisions when faced with sudden changes in the weather variables. The WASE running in parallel to a regular SE will be able to improve the EMS and capture the weather related changes in the power system.

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