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(54) **Title**: ENERGY ARBITAGE USING ENERGY PRICE FORECAST AND WIND POWER FORECAST

(57) **Abstract**: Embodiments of the invention generally relate to wind power plants, and particularly to controllers and control algorithms for wind power plants incorporating an energy storage system. A controller may periodically retrieve wind forecast and energy price forecast data and cause the energy storage system to be charged or discharged based on the forecast data in a manner that increases revenue and reduces cost for the wind power plant operator.

ENERGY ARBITAGE USING ENERGY PRICE FORECAST AND WIND POWER FORECAST

FIELD OF THE INVENTION

Embodiments of the invention generally relate to wind power plants, and particularly to controllers and control algorithms for wind power plants incorporating an energy storage system.

BACKGROUND

In recent years, there has been an increased focus on reducing emissions of greenhouse gases generated by burning fossil fuels. One solution for reducing greenhouse gas emissions is developing renewable sources of energy. Particularly, energy derived from the wind has proven to be an environmentally safe and reliable source of energy, which can reduce dependence on fossil fuels.

Energy in wind can be captured by a wind turbine, which is a rotating machine that converts the kinetic energy of the wind into mechanical energy, and the mechanical energy subsequently into electrical power. Common horizontal-axis wind turbines include a tower, a nacelle located at the apex of the tower, and a rotor that is supported in the nacelle by means of a shaft. The shaft couples the rotor either directly or indirectly with a rotor assembly of a generator housed inside the nacelle. A plurality of wind turbines generators may be arranged together in a wind park/farm or wind power plant to generate sufficient energy to support a grid.

As wind farms continue to proliferate and generate a greater share of the total energy produced, it has become important for wind farms to perform like traditional power plants. Because power production from wind farms is dependent on the availability of wind resources, various types of energy storage systems may be included in the wind farm to store energy and provide the stored energy when the wind resources may be unavailable. In other words, the energy storage systems can make the wind farm more dispatchable, in a manner similar to more traditional power plants.

SUMMARY OF THE INVENTION

Embodiments of the invention generally relate to wind power plants, and particularly to controllers and control algorithms for wind power plants incorporating an energy storage system.

One embodiment of the invention provides a method for operating a wind power plant. The method generally comprises retrieving, for a predefined future period of time, wind forecast data and energy price forecast data, and based on the retrieved wind forecast data and energy price forecast data for the predefined period, determining whether an energy storage system associated with the wind power plant should be charged or discharged during the predefined future period of time.

Another embodiment of the invention provides a controller configured to retrieve, for a predefined future period of time, wind forecast data and energy price forecast data, and based on the retrieved wind forecast data and energy price forecast data for the predefined period, determine whether an energy storage system associated with the wind power plant should be charged or discharged during the predefined future period of time.

Yet another embodiment of the invention provides a wind power plant comprising a wind farm, an energy storage system, and a controller generally configured to retrieve, for a predefined future period of time, wind forecast data and energy price forecast data, and based on the retrieved wind forecast data and energy price forecast data for the predefined period, determine whether the energy storage system should be charged or discharged during the predefined future period of time.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the present invention are explained, by way of example, and with reference to the accompanying drawings. It is to be noted that the appended drawings illustrate only examples of embodiments of this invention and are therefore not to be considered limiting of its scope, for the invention may admit to other equally effective embodiments.

Figure 1 illustrates an exemplary wind turbine according to an embodiment of the invention.

Figure 2 illustrates an exemplary nacelle according to an embodiment of the invention.

Figure 3 illustrates an exemplary wind power plant according to an embodiment of the invention.

Figure 4A illustrates an exemplary decision chart for determining whether an energy storage system should be charged or discharged, according to an embodiment of the invention.

Figure 4B illustrates exemplary wind forecast and energy price forecast data according to an embodiment of the invention.

Figure 5 is a flow diagram of exemplary operations performed by a controller in a time shifting mode, according to an embodiment of the invention.

Figure 6 is a flow diagram of exemplary operations performed by a controller in a transmission curtailment mode, according to an embodiment of the invention.

DETAILED DESCRIPTION

In the following, reference is made to embodiments of the invention. However, it should be understood that the invention is not limited to specific described embodiments. Instead, any combination of the following features and elements, whether related to different embodiments or not, is contemplated to implement and practice the invention.

Furthermore, in various embodiments the invention provides numerous advantages over the prior art. However, although embodiments of the invention may achieve advantages over other possible solutions and/or over the prior art, whether or not a particular advantage is achieved by a given embodiment is not limiting of the invention. Thus, the following aspects, features, embodiments and advantages are merely illustrative and are not considered elements or limitations of the appended claims except where explicitly recited in a claim(s). Likewise, reference to "the invention" shall not be construed as a generalization of any inventive subject matter disclosed herein and shall not be considered to be an element or limitation of the appended claims except where explicitly recited in a claim(s).

The following is a detailed description of embodiments of the invention depicted in the accompanying drawings. The embodiments are examples and are in such detail as to clearly communicate the invention. However, the amount of detail offered is not intended to limit the anticipated variations of embodiments; but on the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the present invention as defined by the appended claims.

With reference to Figures 1 and 2, the following description of wind turbine 10 applies equally to all wind turbines in this specification. Wind turbine 10 includes a tower 12, a nacelle 14 disposed at the apex of the tower 12, and a rotor 16 operatively coupled to a generator 20 housed inside the nacelle 14. In addition to the generator 20, nacelle 14 houses various components needed to convert wind energy into electrical energy and also various components needed to operate and optimize the performance of the wind turbine 10. The tower 12 supports the load presented by the nacelle 14, rotor 16, and other wind turbine components housed inside the nacelle 14. The tower 12 of the wind turbine 10 operates to elevate the nacelle 14 and rotor 16 to a height above ground level or sea level, as may be the case, at which air currents having lower turbulence and higher velocity are typically found.

The rotor 16 includes a central hub 22 and a plurality of blades 24 attached to the central hub 22 at locations distributed about the circumference of the central hub 22. In the representative embodiment, the rotor 16 includes three blades 24. The blades 24, which project radially outward from the central hub 22, are configured to interact with the passing air currents to produce lift that causes the central hub 22 to spin about its longitudinal axis. The design, construction, and operation of the blades 24 are familiar to a person having ordinary skill in the art. For example, pitch angle control of the blades 24 may be implemented by a pitch control mechanism (not shown).

The rotor 16 is coupled by a drive shaft 32 and a gearbox 34 with the rotor assembly of the generator 20. The gearbox 34 relies on gear ratios in a drive train to provide speed and torque conversions from the rotation of the rotor 16 to the rotor assembly of the generator 20. Alternatively, the drive shaft 32 may directly connect the central hub 22 of the rotor 16 with the rotor assembly of the generator 20 so that rotation of the central hub 22 directly drives the rotor assembly to spin relative to a stator assembly of the generator 20. A mechanical coupling 36 provides an elastic connection between the drive shaft 32 and the gear box 34.

The wind turbine 10, which is depicted as a horizontal-axis wind turbine, has the ability to convert the kinetic energy of the wind into electrical power. Specifically, the motion of the rotor assembly of generator 20 relative to the stator assembly of generator 20 functionally converts the mechanical energy supplied from the rotor 16 into electrical power so that the kinetic energy of the wind is harnessed by the wind turbine 10 for power generation. Wind exceeding a minimum level will activate the rotor 16 and cause the rotor 16 to rotate in a direction substantially perpendicular to the wind. Under normal circumstances, the electrical power is supplied to the power grid 40 as known to a person having ordinary skill in the art.

A plurality of wind turbines may be arranged together in a wind power plant (WPP). The power generated by the plurality of wind turbines may be collected and provided to a grid according to one or more requirements of the grid, commonly referred to as grid codes. As wind power plants start to generate a greater portion of the power transmitted on to the grid, it has become crucial that wind power plants emulate the behavior of traditional power plants. However, wind power plants rely on wind resources, which may not be available at all times. Accordingly, many wind power plants may also incorporate energy storage systems that may be configured to store energy which can be utilized for various purposes including, but not limited to, providing power when wind resources are unavailable, facilitating compliance with grid codes, providing back-up power for wind turbine components, and the like.

Figure 3 illustrates an exemplary wind power plant 300 according to an embodiment of the invention. As illustrated, the wind power plant 300 may include a wind farm 310, an energy storage system 320, and a controller 330. The wind farms 310 may include one or more wind turbines, such as the representative wind turbine 10. The wind turbines collectively act as a generating plant ultimately interconnected by transmission lines with a power grid 340, which may be a three-phase power grid. Where the wind farm 310 has more than one turbine, the wind turbines may be gathered together at a common location in order to take advantage of the economies of scale that decrease per unit cost with increasing output. It is understood by a person having ordinary skill in the art that the wind farm 310 may include an arbitrary number of wind turbines of given capacity in accordance with a targeted power output.

The power grid 340 generally consists of a network of power stations, transmission circuits, and substations coupled by a network of transmission lines. The power stations generate electrical power by nuclear, hydroelectric, natural gas, or coal fired means, or with another type of renewable energy like solar and geothermal. Additional wind farms analogous to the wind farm 310 depicted may also be coupled with the power grid 340. Power grids and wind farms typically generate and transmit power using Alternating Current (AC).

The energy storage system 320 may include one or more batteries 321, converter, 322, a sensor 323, and data converter 324, as illustrated in Figure 3. In one embodiment of the invention, the energy storage system 320 may be located at or near the wind 310. However, in alternative embodiments, the energy storage system may be remotely located, for example, several miles from the wind farm 310. In some embodiments, the energy storage system 320 may include storage devices that may exist both at the wind farm 310 and at remote locations. For example, the batteries 321 may include one or more batteries placed at or near one or more respective turbines (e.g., in the nacelle or tower) as well as one or more batteries located at a remote location.

The batteries 321 may store and release electrical energy in the form of Direct Current (DC). Accordingly, a power converter 322 may convert between AC power usable by the wind farm 310 and the power grid 340, and DC power usable by the batteries 321. While batteries 321 are shown in Figure 3, in alternative embodiments, any type of enery storage device, for example, fly wheels, flow batteries, and the like may be included instead of the batteries 321. In some embodiments, a plurality of different types of energy storage devices may be included in the energy storage system 320.

The converter 322 may be electrically connected between the power grid 340 and respective batteries 321, as illustrated. The converter 322 may include active switches, such as power semiconductor devices, in a configuration suitable to transform AC power supplied by wind farm 310 into DC power during times when batteries 322 are storing excess power supplied from the wind farm 310 and to transform DC power into AC power at times when batteries 321 are supplying power to the grid 340. When batteries are charging by storing power received from wind farm 310, converter 322 conditions the output from the wind farm 310 to provide a DC output voltage and current suitable for charging batteries 321. When batteries 321 are providing power to the grid 340, converter 322 conditions the energy discharged by the respective batteries 321 to provide an output voltage and current at a frequency and phase appropriate for transmission to the power grid 340. The design, construction, and operation of the converter 322 is understood by a person having ordinary skill in the art.

At least one sensor 323 is operatively coupled to the batteries 321, as illustrated in Figure 3. The sensor 323 may be configured with one or more sensors to detect and monitor one or more battery operational parameters, including but not limited to voltage, battery current, and temperature, and to generate signals representative of each sensed battery operational parameter. A data converter 324 may receive readings in the form of signals communicated from the sensor 323 and communicate the readings to a controller 330.

The controller 330 can be implemented using one or more processors 331 selected from microprocessors, micro-controllers, digital signal processors, microcomputers, central processing units, field programmable gate arrays, programmable logic devices, state machines, logic circuits, analog circuits, digital circuits, and/or any other devices that manipulate signals (analog and/or digital) based on operational instructions that are stored in a memory 332.

Memory 332 may be a single memory device or a plurality of memory devices including but not limited to read-only memory (ROM), random access memory (RAM), volatile memory, non-volatile memory, static random access memory (SRAM), dynamic random access memory (DRAM), flash memory, cache memory, and/or any other device capable of storing digital information.

Mass storage device 333 may be a single mass storage device or a plurality of mass storage devices including but not limited to hard drives, optical drives, tape drives, non-volatile solid state devices and/or any other device capable of storing digital information. An Input/Output (I/O) interface 334 may employ a suitable communication protocol for communicating with at least the data converter 324.

Processor 331 operates under the control of an operating system, and executes or otherwise relies upon computer program code embodied in various computer software applications, components, programs, objects, modules, data structures, etc. to read data from and write instructions to the data converter 324 through I/O interface 334, whether implemented as part of the operating system or as a specific application.

A human machine interface (HMI) 350 is operatively coupled to the processor 331 of the controller 330 in a known manner. The HMI 350 may include output devices, such as alphanumeric displays, a touch screen, and other visual indicators, and input devices and controls, such as an alphanumeric keyboard, a pointing device, keypads, pushbuttons, control knobs, etc., capable of accepting commands or input from the operator and transmitting the entered input to the processor 331.

The network interface device 360 may be any entry/exit device configured to allow network communications between the controller 330 and a network, e.g., the internet. In one embodiment, the network interface device 360 may be a network adapter or other network interface card (NIC).

In one embodiment of the invention, the controller 330 may be configured to generate power reference signals to the wind farm 310 and the energy storage system 320. For example, in Figure 3, the controller 330 is shown generating a WPP reference signal 311 to the wind farm and an ES reference signal 325 to the Energy storage system. The power reference signal 311 may indicate an amount of power that should be generated by the wind farm 310 based on, for example, the available wind resources. Based on the power reference signal 311 the wind turbines in the wind farm 310 may adjust one or more operational parameters, e.g., blade pitch angles, so that the wind farm produces the power defined by the power reference signal 311. The power reference signal 325 may indicate an amount of power to be discharged from the energy storage system 320 to the grid 320, or may cause the energy storage system to be charged via the grid 340 or the wind farm 310.

As described above, the availability of wind resources may vary over time. Accordingly, a suitable control algorithm is needed to control the discharging of energy from the batteries 321 to the grid 340. As the energy stored in the batteries is depleted, the batteries may need to be charged back up for future use. The charging of the energy storage system may be accomplished by storing the energy generated by the wind farm 310 and/or by purchasing power from the grid 340. Embodiments of the invention provide methods for charging and discharging the energy storage system in a manner that generates maximum revenue and reduce costs for the wind power plant operator.

Figure 3 illustrates a control algorithm 335 residing in memory 332. The control algorithm, when executed by the processor 331 may cause the wind power plant 300 to perform operations related to various aspects of embodiments of the invention. Specifically, the control algorithm may control the charging and discharging of the energy storage system in a manner that maximizes revenues and reduces costs for the wind power plant operator.

As is well known to persons skilled in the art, the price of energy may vary over time. In one embodiment of the invention, to maximize revenue and reduce costs, the controller 330 may be configured to operate the wind power plant in a first mode, which may cause the energy storage system 320 to be charged at times when the price of energy is low, and discharge energy to the grid when the price of energy is high. The first mode is described herein as the time shifting mode.

In one embodiment of the invention, the time shifting mode may be the default mode of operation for the wind turbine. In one embodiment, in the time shifting mode, the controller 330 (while executing the control algorithm 335) may be configured to make the determination to charge or discharge the energy storage system and the amount of energy to be stored in the energy storage system (by setting power reference signal 325) based on wind forecasts and energy price forecasts. The wind forecasts and the energy price forecasts may be retrieved by the controller via the network interface 360 or received via the human-machine interface 350.

Figure 4A illustrates an exemplary decision chart 400 that may be used by the controller 330 to determine whether the energy storage system should be charged or discharged based on forecasted availability of wind resources and forecasted energy prices. As illustrated in row 410 of chart 400, when the forecasted availability of wind resources and the forecasted energy prices are low, the energy storage system 320 may be charged or discharged. In one embodiment, the decision whether to charge or discharge may be based on the state of charge of the energy storage system. The state of charge of the energy storage system may be retrieved by the controller 330 via the sensor 323. In one embodiment, upon determining that the energy storage system has sufficient energy, the controller 330 may cause the energy storage system 320 to discharge energy to the grid 340 to compensate for the lack of (forecasted) availability of wind power. However, if the amount of energy stored in the energy storage system is insufficient, the controller 330 may determine to take advantage of the forecasted low energy prices to charge up the energy storage system. In an alternative embodiment, the controller 330 may always charge the energy storage system to a desired level when the forecasted energy prices are low prior to discharging the energy storage system.

Row 420 of chart 400 illustrates a situation where it is determined that the forecasted availability of wind resources are low and the forecasted price of energy is high. In one embodiment, the controller 330 may discharge the energy storage system to take advantage of the forecasted high energy prices and generate greater revenue for the wind power plant operator. Row 430 of chart 400 illustrates a situation where it is determined that the forecasted availability of wind resources is high but the forecasted price of energy is low. In this situation, because there may be sufficient wind energy to satisfy the grid, the controller 330 may decide to take advantage of the forecasted low energy prices to charge the energy storage system 320.

Row 440 illustrates a situation where it is determined that the forecasted availability of wind resources are high and the forecasted price of energy is also high. In one embodiment, the controller 330 may decide to discharge the energy storage system in this case to take advantage of the forecasted high energy prices. In one embodiment, while there may be sufficient wind power available to satisfy the grid requirements in the case illustrated in row 440, the controller may decide not to take full advantage of the available wind resources. This may be done, for example, to reduce the mechanical wear and tear of wind turbines. In other words, the controller 330 may prefer to provide as much power as possible from the energy storage system in this case to reduce the use of the wind turbines, thereby extending the life of the wind turbines.

One skilled in the art should recognize that the decisions to charge or discharge the energy storage system 320 may depend on one or more characteristics of the energy storage system. For example, the decision to charge or discharge may depend on the state of charge, state of health, capacity, and the like of the batteries 321. As an illustration, the decision to charge the energy storage system in row 430 can only be taken if the energy storage system is not fully charged to a desirable level. Similarly, the decision to discharge the energy storage system in row 420 can only be taken if there is available energy stored in the energy storage system.

In one embodiment of the invention, the controller 330 may be configured to review its decision regarding the charging or discharging of the energy storage system periodically at the end of a predefined period of time. At the end of the predefined period, the controller 330 may retrieve updated wind and energy price forecasts and determine whether the energy storage system should be charged or discharged based on the latest forecast information. The predefined period of time can be any period, for example, 10 minutes, 2-3 hours, weeks, months, or the like.

Figure 4B illustrates an exemplary energy price forecast 452 and wind availability forecast 453 over a time horizon t. Also illustrated in Figure 4B is a threshold level 451. It is assumed, for this example, that energy prices and wind availability above the threshold level 451 are considered high, and that energy prices and wind availability below the threshold level 451 are considered low. In one embodiment, at time t1, the controller 330 may be configured to analyze the forecast data for a future period of time, e.g., from t1 – t2. Because both the wind availability forecast 453 and the energy price forecast 452 are low in the time period between t1 and t2, the controller 330 may decide to either charge or discharge the energy storage system (see row 410 of Figure 4A and related description above).

At time t2, the controller 330 may analyze the energy price forecast 452 and wind availability forecast 453 for the time period from t2 to t3. One skilled in the art will recognize that the forecasts 452 and 453 may have changed since the previous analysis at t1. Referring to Figure 4B, because the wind availability forecast is low and the energy price forecast is high, the controller 330 may determine that the energy storage should be discharged (see row 420 of Figure 4A).

At time t3, the controller 330 may analyze the energy price forecast 452 and wind availability forecast 453 for the time period from t3 to t4. One skilled in the art will recognize that the forecasts 452 and 453 may have changed since the previous analysis at t2. Referring to Figure 4B, because the wind availability forecast is generally high and the energy price forecast is generally low, the controller 330 may determine that the energy storage should be charged (see row 430 of Figure 4A).

Figure 5 is a flow diagram of exemplary operations performed by the controller 330 in the time shifting mode, according to an embodiment of the invention. The operations may begin in step 510 by retrieving updated forecast information. The forecast information retrieved may include, for example, the wind forecast and/or energy price forecast. In one embodiment, the controller may also retrieve data regarding one or more parameters of the energy storage system, e.g., the state of charge, state of health, capacity, and the like in step 510.

In step 520, the controller may determine whether the forecast data is significantly different from previously received forecast data. For example, the controller may determine whether the difference between the previous forecast and the currently retrieved forecast is greater than a predefined threshold. If the difference between the previous forecast and the currently retrieved forecast is not greater than the predefined threshold the operations may enter step 540. However, if the difference between the previous forecast and the currently retrieved forecast is greater than the predefined threshold, the controller may revise its previous determination whether the energy storage system should be charged or discharged, in step 530. The decision whether to charge or discharge may be based on the currently retrieved wind and energy price forecast, as illustrated in the exemplary decision chart in Figure 4A.

In one embodiment, determining whether the current forecast data is significantly different from previously obtained forecast data may involve determining whether a first difference between the current wind forecast data and the previously wind forecast data is greater than a first predefined threshold, and determining whether a second difference between the current energy price forecast data and the previously energy price forecast data is greater than a second predefined threshold. In one embodiment, the determination step 530 may be performed only upon determining that the first difference is greater than the first predefined threshold or that the second difference is greater than the second predefined threshold.

In step 540, the controller may determine whether a predefined period of time has elapsed since the last retrieval of forecast data. If the predefined period has not elapsed, the controller may remain in step 540. When the predefined period of time elapses, the controller may return to step 510, as illustrated in Figure 5.

Some wind power plants may be capable of producing a greater amount of power than is required by the grid. For example, at certain times of the day, energy use may drop on the grid. It is possible that, at these times, ample wind resources are available to produce more power than is needed. Accordingly, the grid may assert one or more signals to the wind power plant requesting that the power generation be curtailed. In other words, the grid may request that the wind power plant produce a lesser amount of power than it is capable of producing.

In one embodiment of the invention, the controller 330 may be configured to operate in a second more referred to herein as the transmission curtailment mode. In the transmission curtailment mode, the controller 330 may be configured to utilize the availability of excess wind power to charge the energy storage system. By charging the energy storage system with excess wind power, the controller 330 may reduce the need for purchasing power from the grid to charge the energy storage system, thereby resulting in significant savings in cost for the wind power plant operator.

Figure 6 is a flow diagram of exemplary operations that the controller 330 may perform in a transmission curtailment mode, according to an embodiment of the invention. The operations may begin in step 610 by detecting a power curtailment command, which may be received from the grid. In response to detecting the power curtailment command, the controller 330 may determine the state of charge of the energy storage system in step 620. If the energy storage system is not charged to a desired level, in step 630, the controller may cause the energy storage system 320 to be charged with curtailed wind power from the wind farm 310 in step 630. For example, the controller 330 may assert a reference signal 325 that may cause the energy storage system to be charged with a portion of the power (curtailed) generated by the wind farm 310.

If the energy storage system is determined to have a desired level of energy stored therein in step 620, the controller 330 may curtail the power produced by the wind farm 310 in step 640. This may be accomplished, for example, via the power reference signal 311. If an end of the curtailment is detected, e.g., via an end of curtailment command from the grid, controller 330 may be configured to exit the transmission curtailment mode and enter a different mode, e.g., the time shifting mode.

In one embodiment of the invention, while curtailing power generated by the wind farm (e.g. step 640 of Figure 6), the controller 330 may operate the wind power plant in time shifting mode. While sufficient wind power is present to satisfy grid requirements during curtailment, it may be desirable to reduce the mechanical wear and tear of the wind turbines of wind farm 310 by providing at least a portion of the power via the fully charged energy storage system 320, particularly during period when energy prices may be high.

While the invention has been illustrated by a description of various embodiments and while these embodiments have been described in considerable detail, it is not the intention of the applicant to restrict or in any way limit the scope of the appended claims to such detail. Additional advantages and modifications will readily appear to those skilled in the art. The invention in its broader aspects is therefore not limited to the specific details, representative methods, and illustrative examples shown and described. Accordingly, departures may be made from such details without departing from the spirit or scope of applicant's general inventive concept.

WHAT IS CLAIMED IS:

1. A method for operating a wind power plant, comprising the following steps:

retrieving, for a predefined future period of time, wind forecast data and energy price forecast data; and

based on the retrieved wind forecast data and energy price forecast data for the predefined period, determining whether an energy storage system associated with the wind power plant should be charged or discharged during the predefined future period of time.

2. The method of claim 1, further comprising, at the end of the predefined future period of time:

(a) retrieving updated wind forecast data and updated energy price forecast data for a next predefined future period of time;

(b) based on the retrieved updated wind forecast data and the updated energy price forecast data for the predefined period, determining whether the energy storage system associated with the wind power plant should be charged or discharged during the next predefined future period of time.

3. The method of claim 2, further comprising:

comparing the updated wind forecast data and updated energy price forecast data with the wind forecast data and the energy price forecast data; and

performing step (b) only upon determining that the comparison exceeds a threshold level.

4. The method of claim 1, further comprising generating a first power reference signal to a wind farm of the wind power plant and generating a second power reference to the energy storage system based on determining whether the energy storage system should be charged or discharged during the predefined future period of time.

5. The method of claim 1, further comprising:

detecting a power curtailment command;

in response to detecting the power curtailment command, determining whether the energy storage system is charged to a desirable level;

upon determining that the energy storage system is not charged to a desirable level, charging the energy storage system with curtailed wind power from a wind farm of the wind power plant; and

upon determining that the energy storage system is charged to a desirable level, curtailing wind power produced by the wind farm.

6. The method of claim 1, further comprising repeating steps (a), (b) and (c) once every predefined period of time.

7. A controller configured to:

retrieve, for a predefined future period of time, wind forecast data and energy price forecast data; and

based on the retrieved wind forecast data and energy price forecast data for the predefined period, determine whether an energy storage system associated with the wind power plant should be charged or discharged during the predefined future period of time.

8. The controller of claim 7, further configured to, at the end of the predefined future period of time:

(a) retrieve updated wind forecast data and updated energy price forecast data for a next predefined future period of time;

(b) based on the retrieved updated wind forecast data and the updated energy price forecast data for the predefined period, determine whether the energy storage system associated with the wind power plant should be charged or discharged during the next predefined future period of time.

9. The controller of claim 8, further configured to:

compare the updated wind forecast data and updated energy price forecast data with the wind forecast data and the energy price forecast data; and

perform step (b) only upon determining that the comparison exceeds a threshold level.

10. The controller of claim 7, further configured to generate a first power reference signal to a wind farm of the wind power plant and generate a second power reference to the energy storage system based on determining whether the energy storage system should be charged or discharged during the predefined future period of time.

11. The controller of claim 7, being further configured to:

detect a power curtailment command;

in response to detecting the power curtailment command, determine whether the energy storage system is charged to a desirable level;

upon determining that the energy storage system is not charged to a desirable level, charge the energy storage system with curtailed wind power from a wind farm of a wind power plant; and

upon determining that the energy storage system is charged to a desirable level, curtail wind power produced by the wind farm.

12. The controller of claim 7, wherein the controller is configured to repeat steps (a), (b) and (c) once every predefined period of time.

13. A wind power plant, comprising:

a wind farm;

an energy storage system; and

a controller configured to:

retrieve, for a predefined future period of time, wind forecast data and energy price forecast data; and

based on the retrieved wind forecast data and energy price forecast data for the predefined period, determine whether the energy storage system should be charged or discharged during the predefined future period of time.

14. The wind power plant of claim 13, wherein the controller is further configured to, at the end of the predefined future period of time:

(a) retrieve updated wind forecast data and updated energy price forecast data for a next predefined future period of time;

(b) based on the retrieved updated wind forecast data and the updated energy price forecast data for the predefined period, determine whether the energy storage system associated with the wind power plant should be charged or discharged during the next predefined future period of time.

15. The wind power plant of claim 14, wherein the controller is further configured to:

compare the updated wind forecast data and updated energy price forecast data with the wind forecast data and the energy price forecast data; and

perform step (b) only upon determining that the comparison exceeds a threshold level.

16. The wind power plant of claim 13, wherein the controller is further configured to generate a first power reference signal to a wind farm of the wind power plant and generate a second power reference to the energy storage system based on determining whether the energy storage system should be charged or discharged during the predefined future period of time.

17. The wind power plant of claim 1, wherein the controller is further configured to:

detect a power curtailment command;

in response to detecting the power curtailment command, determine whether the energy storage system is charged to a desirable level;

upon determining that the energy storage system is not charged to a desirable level, charge the energy storage system with curtailed wind power from a wind farm of a wind power plant; and

upon determining that the energy storage system is charged to a desirable level, curtail wind power produced by the wind farm.

18. The wind power plant of claim 1, wherein the controller is configured to repeat steps (a), (b) and (c) once every predefined period of time.

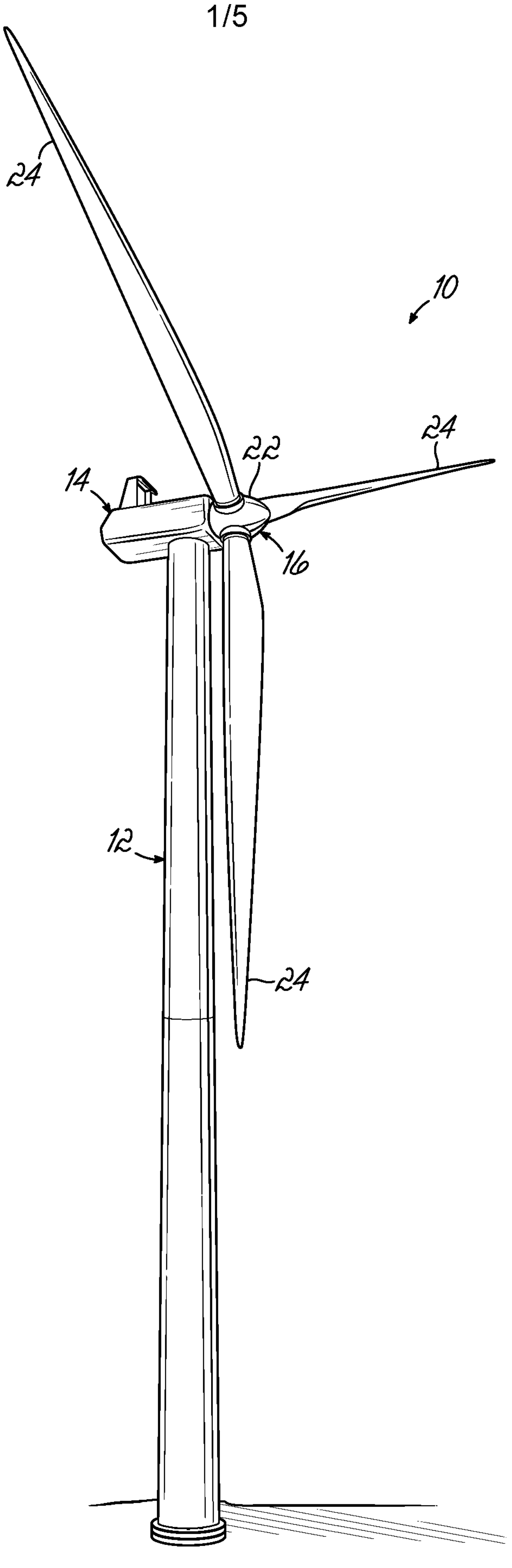


FIG. 1

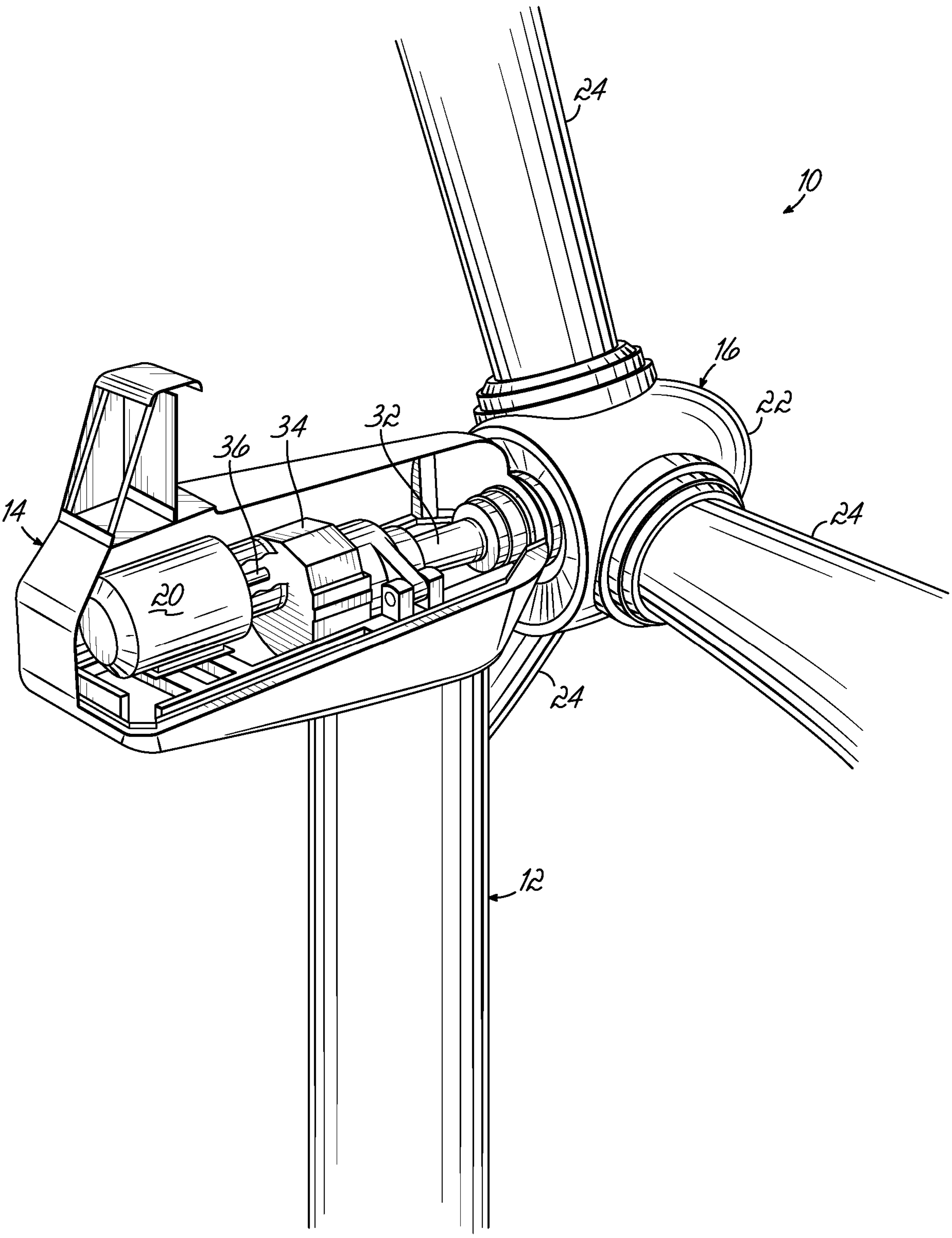
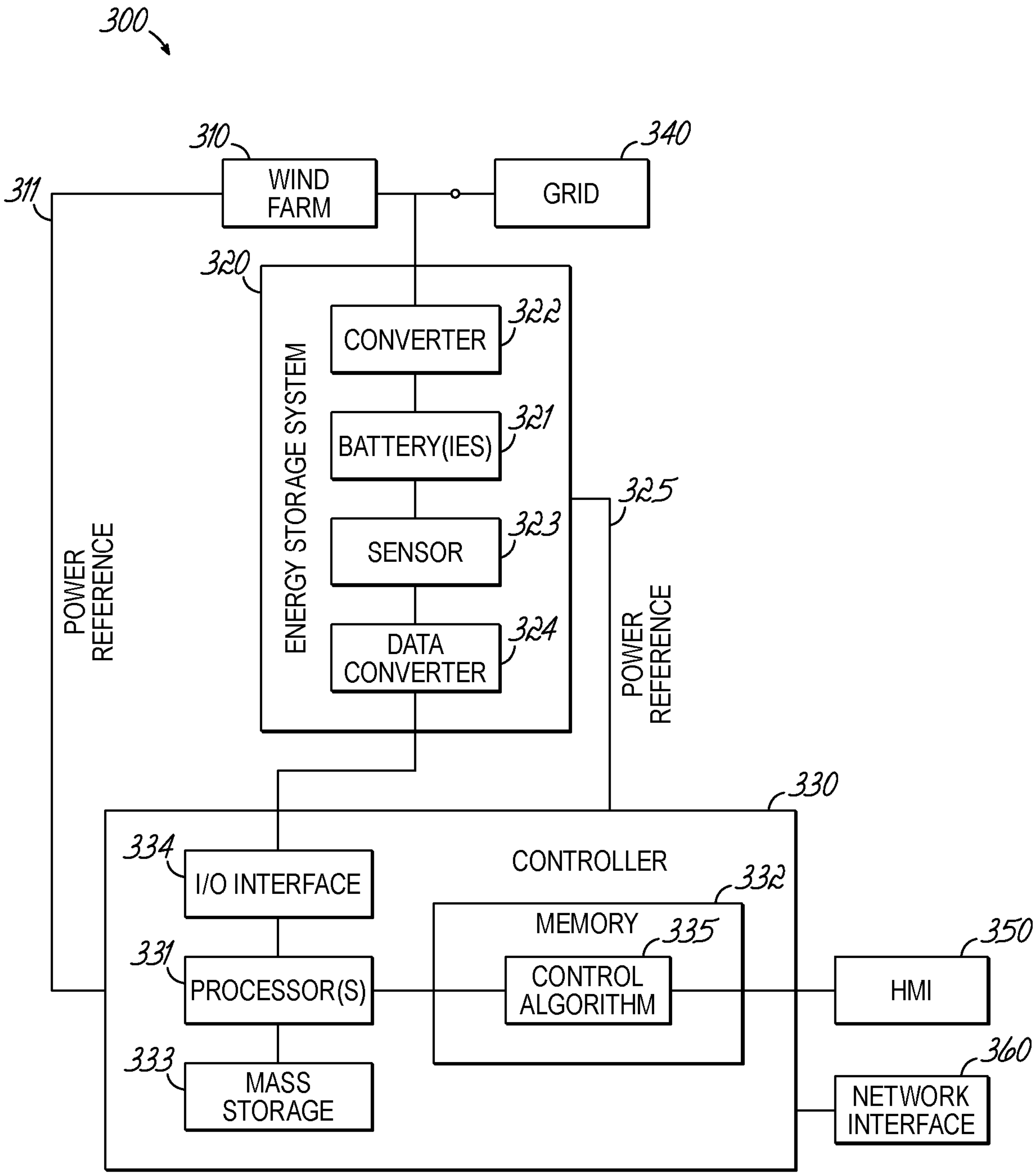


FIG. 2



300
310
WIND FARM
340
GRID
311
POWER REFERENCE
320
ENERGY STORAGE SYSTEM
CONVERTER
322
BATTERY(IES)
321
SENSOR
323
DATA CONVERTER
324
325
POWER REFERENCE
330
CONTROLLER
334
I/O INTERFACE
331
PROCESSOR(S)
333
MASS STORAGE
332
MEMORY
335
CONTROL ALGORITHM
350
HMI
360
NETWORK INTERFACE

FIG. 3

400

	FORECASTED AVAILABILITY OF WIND RESOURCES	FORECASTED PRICE OF ENERGY	DECISION
410	LOW	LOW	CHARGE OR DISCHARGE
420	LOW	HIGH	DISCHARGE
430	HIGH	LOW	CHARGE
440	HIGH	HIGH	DISCHARGE

FIG. 4A

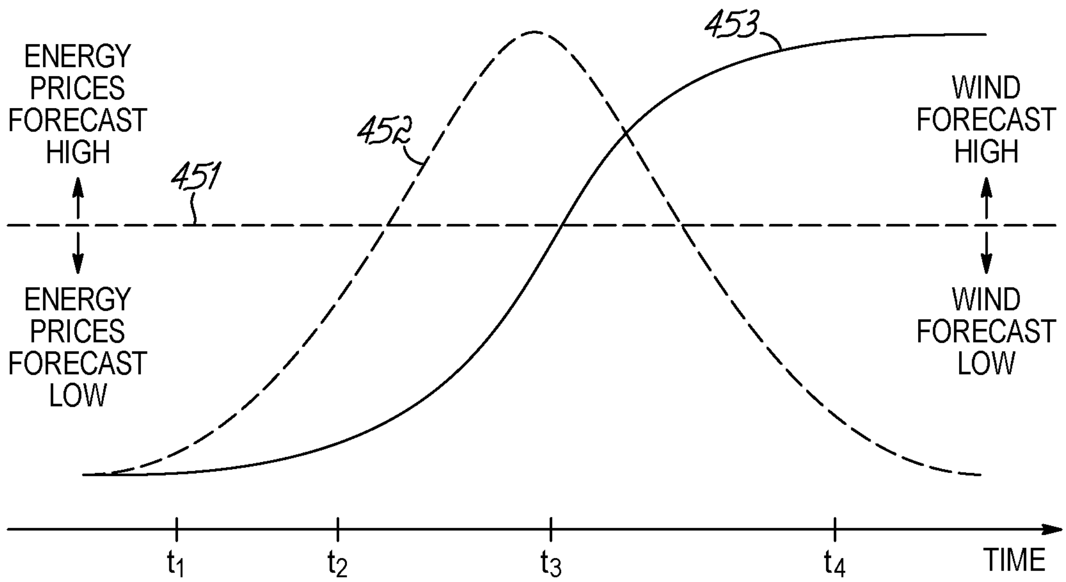


FIG. 4B

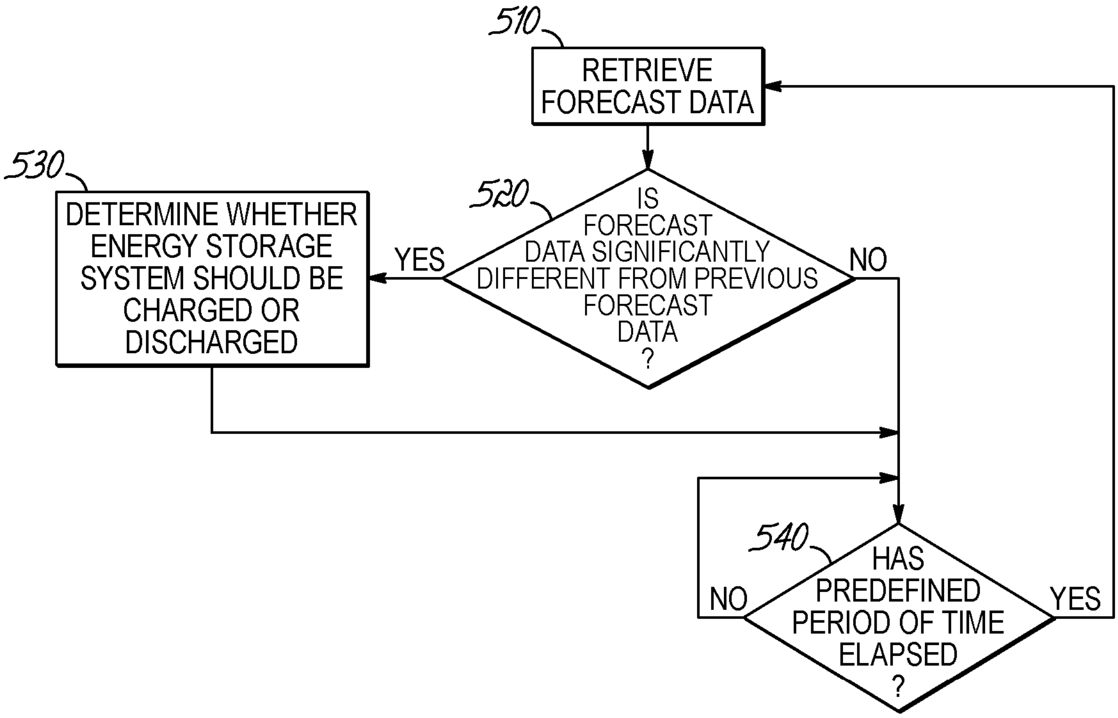

510
RETRIEVE FORECAST DATA
520
IS FORECAST DATA SIGNIFICANTLY DIFFERENT FROM PREVIOUS FORECAST DATA ?
YES
NO
530
DETERMINE WHETHER ENERGY STORAGE SYSTEM SHOULD BE CHARGED OR DISCHARGED
540
HAS PREDEFINED PERIOD OF TIME ELAPSED ?
NO
YES

FIG. 5

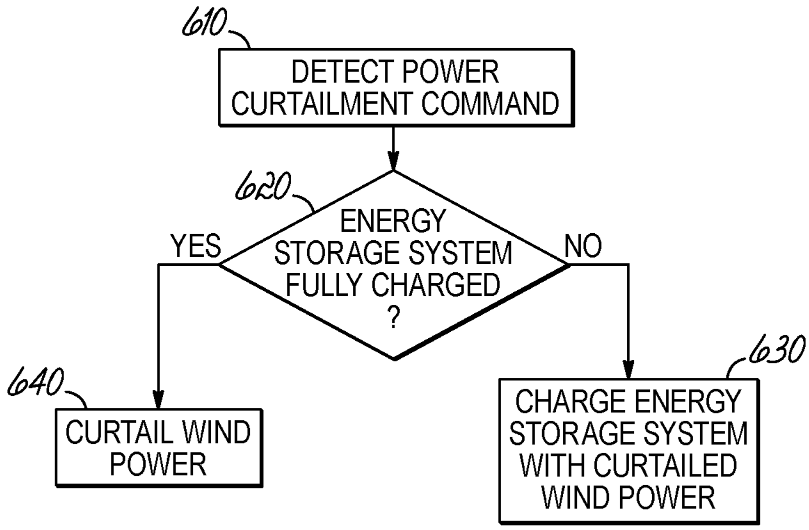

610
DETECT POWER CURTAILMENT COMMAND
620
ENERGY STORAGE SYSTEM FULLY CHARGED ?
YES
NO
640
CURTAIL WIND POWER
630
CHARGE ENERGY STORAGE SYSTEM WITH CURTAILED WIND POWER

FIG. 6