ANALYSIS OF FUZZY LOGIC BASED FREQUENCY
CONTROLLER FOR WIND FARMS AUGMENTED WITH
ENERGY STORAGE SYSTEM

1Dr.N.BHOOPAL,2R.AKHILA
1Professor, B.V.RAJU INSTITUTE OF TECHNOLOGY (Autonomous), Narsapur, Telangana, India.
2M.Tech, B.V.RAJU INSTITUTE OF TECHNOLOGY (Autonomous), Narsapur, Telangana, India

Abstract—To improve the primary frequency response in future low-inertia hybrid power system a fuzzy-logic based frequency controller (FFC) for wind farms augmented with energy storage systems (wind-storage system) is proposed in this paper. Using system frequency deviations the proposed controller provides bidirectional real power injection and rate of change of frequency (RoCoF). Displacement of conventional synchronous generators by non-inertial units such as wind or solar generators will result in reduced-system inertia affecting under-frequency response. Frequency control is important to avoid equipment damage, load shedding, and possible blackouts. To improve the frequency response of low-inertia power system Wind generators along with energy storage systems can be used. Moreover, FFC ensures optimal use of energy from wind farms and storage units by eliminating the inflexible de-loading of wind energy and minimizing the required storage capacity. The efficacy of the proposed FFC is verified by using the simulation results on the low-inertia hybrid power system.

I. INTRODUCTION

The ever increasing demand for energy is one of the biggest challenges in the world today. There are several issues regarding large scale introduction of renewable energy sources. One of the issues is the quality of supply. The utilization of renewable energy sources (RES), which are environmental friendly and inexhaustible, is increasing worldwide. RES including wind, solar, biomass, and geothermal have great potential to be used in large quantities in the future power systems. Large scale wind energy, in particular, has seen unprecedented growth. However, the system frequency response is adversely affected due to increasing penetration of asynchronous wind generators, which have limited ability to provide inertial response. Hence, additional provisions are necessary to enable wind generators so that they can provide frequency response like conventional synchronous generators. Operating wind turbines below maximum power point tracking (MPPT) curve, also known as de-loading operation, can be one of the waysto provide inertial response. The key idea is to use kinetic energy stored in the rotor for the frequency control. The de-loading operation using proportional integral rotor speed and pitch angle controller is proposed. The genetic algorithm based optimization of control parameters for improved frequency response is presented in [5], which is further improved using MIMO linear quadratic Gauss controller [6]. Although pragmatic, these methods require the spillage of wind energy due to de-loading operation. Augmenting wind farms with energy storage systems can be another, yet effective way to provide system frequency response [7]. Recently, frequency regulation using battery energy storage system (BESS) is proposed [8] and improved control performance standards are achieved by integrating BESS with AGC.

The fuzzy Logic Controller (FLC) is applied in the proposed micro grid supply system. The input and output membership functions of fuzzy control contain five grade VL (very low), L (low), M (medium), H (high) and VH (very high). FLC is used to decide the optimum operation of the micro grid system with different mode of operation i.e., i) DG mode ii) gasifier mode iii) Battery charging/discharging mode iv) grid mode14,15. FLC is also used for battery management system which maintains the SOC at reasonable level.

Fig. 1. Frequency response period metrics

As various economic constraints often limit the integration of fast-responsive storage systems, there is a need of advance control scheme to manage wind-storage systems. This paper proposes a new control scheme for wind-storage systems to provide system frequency support, which complements the fast-slow coordinated control for reliable power system operation. Recently, heuristic based controllers have been proposed as an effective way for providing frequency support. The fuzzy-logic based controller, in particular, helps in modeling
complex system behavior, where the direct relationship between system input and output cannot be expressed through equations, by utilizing human understanding. Therefore, this paper utilizes various signals such as system frequency deviations, rate of change of frequency (RoCoF), wind speed (ws), and state of change (SoC) to design a simple fuzzy-logic based controller enabling primary frequency response from wind-storage systems.

II. CURRENT INDUSTRY PRACTICES AND FUTURE TRENDS

Typically, the independent system operator (ISO) has the responsibility to maintain the grid frequency by balancing generation and load. Primary frequency control is considered as an inherent feature of the traditional power system, and governor action is used to control the energy input into the generators’ prime mover. The main aim of the primary frequency control is to reduce the maximum frequency excursion and RoCoF (Fig. 1). Recent replacement of conventional generators by wind has affected the overall system primary frequency response as wind is traditionally unable to respond to frequency deviations.

Fig. 2. FFC based wind-storage system.

Recently, several ISOs use the proportionality automatic generation control (AGC) participation response, where the required AGC signal is divided between energy storage systems and conventional units equally on a per-MW basis. PJM is using dynamic regulation control point based on AGC signal [20], whereas, New York ISO uses state of charge signal to identify a real-time dispatch set point for frequency regulation [21]. Midcontinent ISO uses short-term stored energy resources having high ramp rate such as flywheels.

III. FFC BASED WIND-STORAGE SYSTEMS

A typical wind-storage system consists of several wind generators along with energy storage systems in a geographically close location and connected to the main grid via the point of common coupling (PCC). The proposed FFC control block for a wind-storage system provides frequency response as per frequency deviations and RoCoF, as shown in Fig. 2. Various signals such as ws, and SoC are used as inputs to the FFC controller, which enables wind-storage system to improve the system frequency response. Depending on the available and from wind-storage system, FFC generates command signal and to make wind-storage system produce the change in real power.

Fig. 3. Hybrid system including wind-energy storage system control methods/algorithms for existing and future wind farms for improved primary frequency response. Therefore, this paper proposes the fuzzy-logic based frequency controller (FFC) for wind-storage system for enhanced frequency response. The proposed controller ensures the effective utilization of wind-storage system by controlling and RoCoF during arresting time and prevent under-frequency load shedding.

Fig. 4. Block-diagram of FFC based wind-storage systems.
The value of , whereas, is decided by and is confined by SoC. Therefore, the nonlinear relationship between inputs and outputs of the FFC can be expressed as in (1) and (2)

\[
\begin{align*}
\Delta P_{wss,w} &= g(ws\Delta f, P_{w\max}) \\
\Delta P_{wss,s} &= h(P_{\text{ref}}, \Delta f/\Delta t, \text{SoC})
\end{align*}
\]  

where and are nonlinear functions of FFC controller. is the maximum wind power that can be obtained using maximum power point tracking (MPPT) and is dependent on ws. represents the energy from/to the battery banks. The contribution to virtual inertia and change in frequency due to change in real power from wind and wind storage system can be expressed as (3) and (4), respectively

\[
\begin{align*}
\Delta I &= \frac{1}{2} \left( \frac{L_s}{\Delta f} \right) * \Delta P_{wss,w} \\
\Delta f &= -\left( \Delta P_{wss,w} + \Delta P_{wss,s} \right) * R
\end{align*}
\]  

where is the system nominal frequency (50 Hz); is the coefficient of frequency droop and is assumed as 5%. The total change in real power from the wind-storage system is the sum of and .

In addition, the hybrid power system consists of thermal generators, hydro generators, and large-scale wind-storage systems. The penetrations of each generator are 60%, 20%, and 20%, respectively. Therefore, FFC based wind-storage system is able to have primary frequency response. Specifically, FFC consists of wind energy control block and comparator block, supported by MPPT controller in wind generator, load-frequency controller, and SoC controller in battery banks. At last, the comparator block uses signals from wind energy control block, MPPT value, and SoC enabling the wind-storage system to respond to the variations in system frequency and wind speed.

A. Wind Energy Control Block

The amount of wind energy that can be supplied to the grid and maintain the frequency stability is determined by wind energy control block using ws and .

The open loop response of the fuzzy-logic based control block for different is compared with that of a traditional proportional controller (using “”). Fig. 5 shows that there is much more flexibility to change

\[
\begin{align*}
\Delta f &= -\left( \Delta P_{wss,w} + \Delta P_{wss,s} \right) * R
\end{align*}
\]

\[
\begin{align*}
P_{\text{ref}} &= P_{\text{w, minat}} * (\gamma_1 + \gamma_2) \\
P_{\text{w, minat}} &= 0.9 * P_{\text{w, max}}
\end{align*}
\]

The open loop response of the fuzzy-logic based control block for different is compared with that of a traditional proportional controller (using “”). Fig. 6 shows that there is much more flexibility to change

\[
\begin{align*}
\Delta f &= -\left( \Delta P_{wss,w} + \Delta P_{wss,s} \right) * R
\end{align*}
\]

\[
\begin{align*}
P_{\text{ref}} &= P_{\text{w, minat}} * (\gamma_1 + \gamma_2) \\
P_{\text{w, minat}} &= 0.9 * P_{\text{w, max}}
\end{align*}
\]
B. Wind Generator

With MPPT Block The MPPT controller helps in determining the maximum power available in every wind generator. The block diagram of the DFIG based wind generator model is also shown in Fig. 4. The rotor speed control and pitch angle control are used when wind speed values are below and above the rated speed, respectively. The output of wind turbine is determined.

The operating point of wind generators, such as maximum power point, can be obtained using the inversion of (9) and can be represented using (12):

\[ \alpha \left( \frac{2 \cdot P_{elec}}{\eta_{w,w}} \cdot \theta \right) \]  

(9)

C. Load-Frequency Control

Block of Battery Banks In wind-storage system, battery banks are connected to power system through power converter. BESS store the energy from the wind farms and participates in the frequency control. represents the output of BESS in both discharging/charging operations periods.

Fig. 7. Dynamic model of a typical 3.6 MW DFIG-wind generator block

BESS is sensitive to system frequency deviations in discharging operation period when the SoC is within the range. On the other hand, energy saved in BESS in charging operation period is from wind generators. Moreover, SoC is highly related to the energy accumulated in battery banks which can be explained in (13) and (14):

\[ W_{i+1} = W_i + \eta_{c} \cdot P_{c}^+ \cdot \Delta t \]  

\[ W_{i+1} = W_i + \eta_{d} \cdot P_{d}^+ \cdot \Delta t \]  

where are the energy stored in BESS at time and is the output power of BESS at time , which is positive in (10) and is negative in (11), is the time interval and are charging efficiency and discharging efficiency of BESS and are chosen as 0.95 and 0.65, respectively. The SoC is maintained between 30% and 95% [30]. Frequency dead-band is another important part in the block. When the changes in system frequency are within frequency dead-band, BESS do not provide energy to the system [31], effectively reducing the charging and discharging cycles of BESS and the battery capacities.

D. Comparator

Block Comparator block uses signals generated from wind energy control block, MPPT block, and battery loadfrequency block to determine the change in power from wind and storage units as follows:

- **Scenario #1:**
  \[ R_o C_o F \leq 0.5 \frac{Hz}{s}, \text{and } P_{w,max} \geq P_{w,ref} \]
  Wind generator is able to supply enough power, and the extra power from wind generator is stored in BESS.

- **Scenario #2:**
  \[ R_o C_o F \leq 0.5 \frac{Hz}{s}, \text{and } P_{w,max} < P_{w,ref} \]
  More power is required from wind generators and BESS are plugged in to provide more energy according to the system frequency deviation.

- **Scenario #3:**
  \[ R_o C_o F \geq 0.5 \frac{Hz}{s} \]
  BESS are plugged into the system before frequency drop reaches the frequency dead band.

Fig. 8. Wind turbine reverse block.

where indicates the maximum power that can be produced from the wind farms using MPPT; is the power available from BESS; is the nominal wind farm power that is being produced at a given time; and are the charging and discharging power of
BESS. Therefore, the FFC based wind-storage system ensures that there is no wind spillage and eliminates the need of additional fast-responding energy storage devices, which may be required otherwise due to large-scale intermittent generation in the system.

IV. DYNAMIC MODEL OF WIND-STORAGE SYSTEM

The dynamic model of wind-storage system consists of DFIG based wind generator and BESS block. The transfer function of wind generator is shown in Fig. 7, and is used to determine . The wind turbine block uses (9)–(11), and the wind turbine reverse block (Fig. 8) uses (12). A dynamic model of BESS with frequency dead-band and SoC control is summarized as in Fig. 9. The BESS load-frequency model is used to determine needed for discharging mode of operation [32]. SoC is modeled as the time integral of and is limited to operate between [0.3, 0.95]. The values of all parameters of the wind generator and BESS model are listed in the Appendix.

V. FUZZY LOGIC CONTROLLER

FLC is one of the most successful operations of fuzzy set theory. Its chief aspects are the exploitation of linguistic variables rather than numerical variables. FL control technique relies on human potential to figure out the system behavior and is constructed on quality control rules. The basic structure of an FLC is represented in Fig. 6.

- A Fuzzification interface alters input data into suitable linguistic values.
- A Knowledge Base which comprises of a data base along with the essential linguistic definitions and control rule set.
- A Decision Making Logic which collects the fuzzy control action from the information of the control rules and the linguistic variable descriptions
- A Defuzzification interface which surrenders a non fuzzy control action from an inferred fuzzy control action. In this paper, an advanced control strategy, FLC is implemented along with UPQC for voltage correction through Series APF and for current regulation through Shunt APF. Error and Change in Error are the inputs and Duty cycle is the output to the Fuzzy Logic Controller as shown in Fig. 7.

V. SIMULATIONS AND DISCUSSIONS

The efficacy of the proposed FFC controller is investigated using a hybrid power system as shown. It is clear that the FFC block can improve the descent of wind generator outputs after sudden change in wind speed.

Then, the efficacy of BESS is tested by observing the system under-frequency response after change in wind speed from 8.5 m/s to 7.5 m/s. As the frequency dead-band is set at Hz, the BESS starts supplying the energy as soon as the system frequency falls below 49.9 Hz. Hence, the is improved from 49.94 Hz to 49.98 Hz due to BESS controller. Although both Powss.wand improve the system frequency performance, affects the inertial response due to the fast response time of wind generator.

Performance of FFC Based Wind-Storage Systems

The improvement in under-frequency response using FFC based wind-storage system can be demonstrated using simulations in three different cases as shown in Table II. A step increase of 0.4% p.u. in the load at s causes frequency dip of 0.16 Hz in case#1 as shown in Fig. 13.
Different Scenarios to Investigate the Efficacy of FFC Based Wind-Storage Systems

<table>
<thead>
<tr>
<th>Case #1</th>
<th>Only conventional plants respond to inertial support</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case #2</td>
<td>In addition to conventional plants, wind farms respond to the frequency support using wind energy control block</td>
</tr>
<tr>
<td>Case #3</td>
<td>In addition to conventional plants and wind farms, BESS provide frequency using FFC</td>
</tr>
</tbody>
</table>

VI. CONCLUSION

This paper proposes a fuzzy-logic based frequency controller (FFC) for wind farms augmented with energy storage systems (wind-storage system) to improve the primary frequency response in future low-inertia hybrid power system. Increasing penetration of non-inertial wind generators has inevitably replaced the conventional generators in the recent times. Higher system frequency fluctuations are anticipated due to reduced system inertia making it harder to maintain reliability standards. This paper investigates the frequency control aspect of low inertia hybrid power system and proposes a new FFC for wind farms augmented with energy storage systems. The proposed controller enables wind-storage system to respond to fluctuations in system frequency and wind speed and improves RoCoF as well as of the system. Moreover, FFC ensures optimal utilization of energy from wind farms and storage units by eliminating the inflexible de-loading of wind energy and minimizing the required storage capacity for the given level of frequency support.

<table>
<thead>
<tr>
<th>Approaches Details</th>
<th>$\Delta$LOADING ($\times 10^{-5}$ p.u.)</th>
<th>$\Delta$PRESS ($\times 10^{-5}$ p.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method #1 (De-loading from wind generators, maximum 10% of $P_{max}$)</td>
<td>4.08</td>
<td>0</td>
</tr>
<tr>
<td>Method #2 (De-loading from wind generators, maximum 10% of $P_{max}$ with BESS)</td>
<td>3.50</td>
<td>3.5</td>
</tr>
<tr>
<td>Method #3 (BESS supporting without de-loading from wind generators)</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>Method #4 (Linear controller for wind-storage systems)</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Method #5 (The proposed FFC controller for wind-storage systems)</td>
<td>0</td>
<td>1.5</td>
</tr>
</tbody>
</table>
REFERENCES


Dr. N. BHOOPAL
E-mail id: bhoopal.neerudi@bvrit.ac.in

RAKHILA
Completed B.Tech in Electrical & Electronics Engineering in 2013 from MRCEW affiliated to JNTUH, and Pursuing M.Tech form Padmasri B.V.Raju Institute of Technology (Autonomous), Narsapur, Telangana, India. Area of interest includes Electrical Power Systems.
E-mail id: akhilarangampeta5@gmail.com