Fuzzy-Logic Based Frequency Controller for Wind Farms Augmented With Energy Storage and PV Systems

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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) and intelligent PV farms for the frequency stabilization 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.

Keywords: Battery energy storage system, DFIG-based wind generator, fuzzy logic control, low-inertia hybrid power system, primary frequency control.

1. 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 ways to 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.

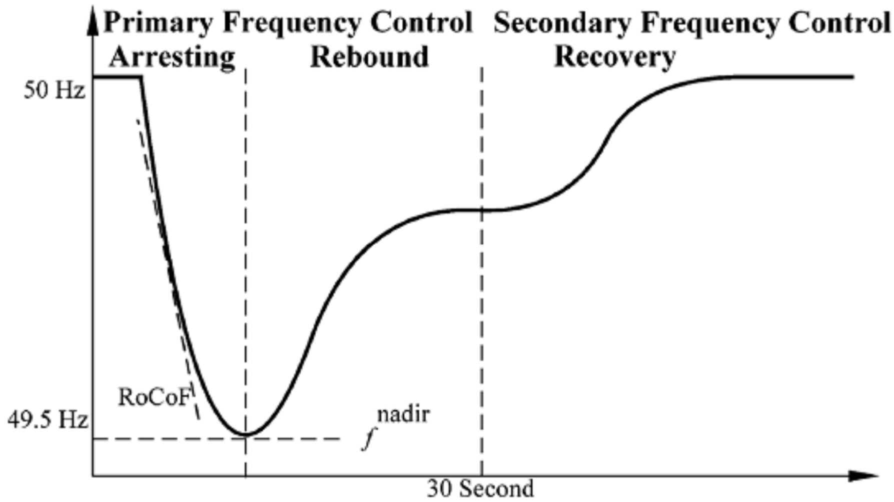

Fig. 1. Frequency response period metrics

2. 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 [19] as wind is traditionally unable to respond to frequency deviations. Traditionally, governor control of fast ramping power plants is used for frequency regulation. Continuous fluctuations in system frequency causes steady state error in tie-line flows and requires constant monitoring through frequency regulation signals, which aims at minimizing the area control error.

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 [22]. Also, authors in [23] have proposed dynamic calculation of AGC signals for energy storage systems for enhancing frequency regulation.

Similarly, distributed frequency regulation services using prosumer based energy storage devices [24] and randomized demand response [25] has been proposed.

All the studies above are focused on utilizing storage systems along with properly designed incentives from ancillary services market to improve frequency regulation [26].

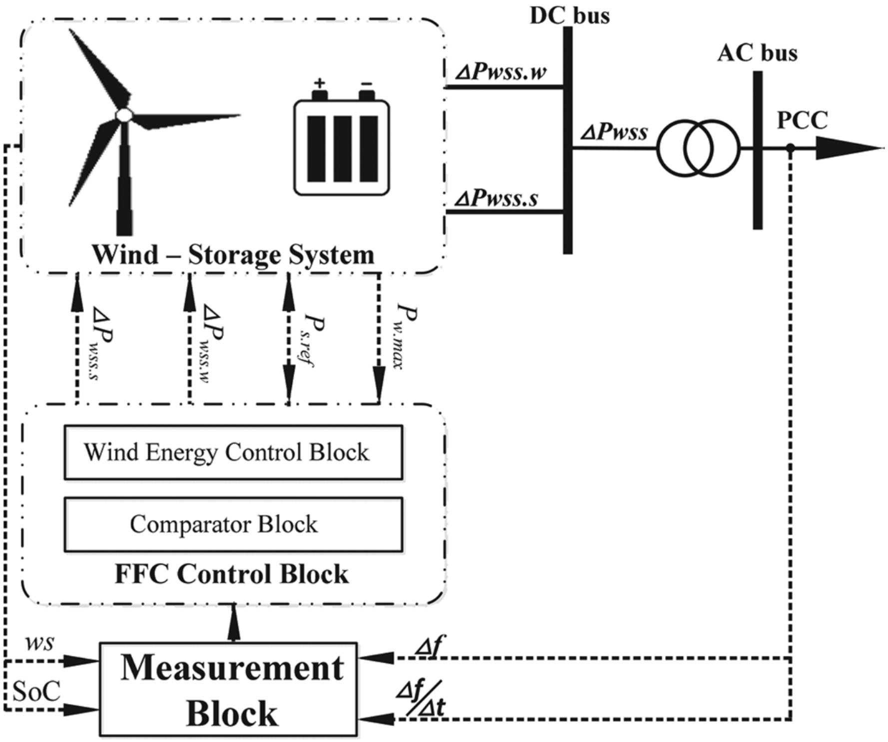

Fig. 2. FFC based wind-storage system.

This paper, whereas, investigates the need for improving primary frequency response due to reduced system inertia. With the increasing penetration of wind generators in the grid, ISOs require new 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.

3. 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 Δf ,$\Delta f\ /\ \Delta t$,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 $P_{s.ref}$ and $P_{w.\max}$ from wind storage system, FFC generates command signal $\Delta P_{wss.w}$ and $\Delta P_{wss.s}$ to make wind-storage system produce the change in real power. In fact $\Delta P_{wss.w}$, and $\Delta P_{wss.s}$ are the power from the wind generator and BESS, respectively.
the value of $\Delta P_{wss.w}$ is a function of Δf and is confined by $P_{w.\max}$.
The value of $\Delta P_{wss.s}$, whereas, is decided by $P_{s.ref}$ and and $\Delta f\ /\ \Delta t$ is confined by SoC. Therefore, the nonlinear relationship between inputs and outputs of the FFC can be expressed as in (1) and (2)

$$\Delta P_{wss.w} = g(ws\Delta f, P_{w.max}) \tag{1}$$

$$\Delta P_{wss.s} = h(P_{s.\mathrm{ref}}\Delta f/\Delta t, \mathrm{SoC}) \tag{2}$$

where and are nonlinear functions of FFC controller. $P_{w.\max}$ is the maximum wind power that can be obtained using maximum power point tracking (MPPT) and is dependent on ws.

$P_{s.ref}$ represents the energy from/to the battery banks. The contribution to virtual inertia (ΔH) and change in frequency (Δf) due to change in real power from wind ($\Delta P_{wss.s}$) and wind storage system (ΔP_{wss}) can be expressed as (3) and (4), respectively:

$$\Delta \mathrm{H} = \frac{1}{2}\left(\frac{\mathrm{f_n} \times \Delta \mathrm{t}}{\Delta \mathrm{f}}\right) \times \Delta \mathrm{P_{wss.w}} \tag{3}$$

$$\Delta f = -(\Delta \mathrm{P_{wss.w}} + \Delta \mathrm{P_{wss.s}}) \times \mathrm{R} \tag{4}$$

Where f_n is the system nominal frequency (50 Hz); R is the coefficient of frequency droop and is assumed as 5%. The total change in real power from the wind-storage system (ΔP_{wss}) is the sum of $\Delta P_{wss.w}$ and $\Delta P_{wss.s}$.

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. In order to highlight the FFC controller, the same kinds of generators are equivalent to one generator as in Fig. 3. ΔP_{wss} is the total power support with FFC.

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. The schematic of the proposed controller is shown in Fig. 4 and is explained as follows.

PV model

Fig. 3 delineates the PV block diagram which consists of PV array, DC/DCconverter, MPPT control, DC/AC converter, battery and SFLC. Note that ISO is a solar insolation, PPV is a PV output power, Pconv is DC/DC converter output power, Pinv is DC/AC converter output power, Iref is a reference current signal from the MPPT control, Pb is a battery power and Ma is a command signal of the SFLC.

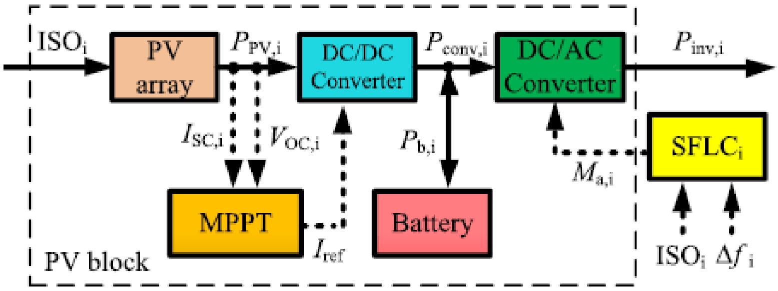

Fig.3. PV block diagram

A current source is used to model the PV module as depicted in Fig.4 .The PeV and IeV characteristic curves of the PV module are illustrated in Fig. 5a and b, respectively. The equation of current in this circuit can be expressed by

$$I_o = I_g - I_{sat}\left\{\exp\left[\frac{q}{AKT}(V_o + I_oR_s)\right] - 1\right\} \quad (5)$$

where, Io and Vo are an output current and an output voltage of the PV module, respectively, Ig is a generated current under the given insolation, Isat is a reverse saturation current, q is a charge of an electron, K is the Boltzmann's constant, A is an ideality factor for the pen junction, T is a temperature (K), and Rs is an intrinsic series resistance of the PV module.

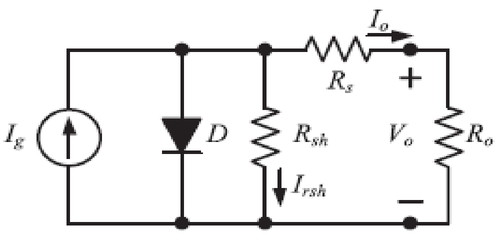

Fig.4. PV equivalent circuit.

The saturation current (Isat) of the PV module which varies with the temperature, is given by.

$$I_{sat} = I_{or}\left[\frac{T_{mod}}{T_r}\right]^3 \exp\left[\frac{qE_g}{KT_{mod}}\left(\frac{1}{T_r} - \frac{1}{T_{mod}}\right)\right] \quad (6)$$

And

$$I_g = I_{sc}\frac{ISO}{1000} + I_t(T_{mod} - T_r) \quad (7)$$

where Tr is a reference temperature (K), Ior is a saturation current at Tr, Tmod is a temperature of the PV module (K), Eg is a band-gap energy and it is a short circuit current temperature coefficient. The current flow in the shunt resistance is provided by

$$I_{rsh} = \frac{V_o}{N_sR_{sh}} \quad (8)$$

where Rsh is an internal shunt resistance of the PV module and Ns is a number of cells in series.

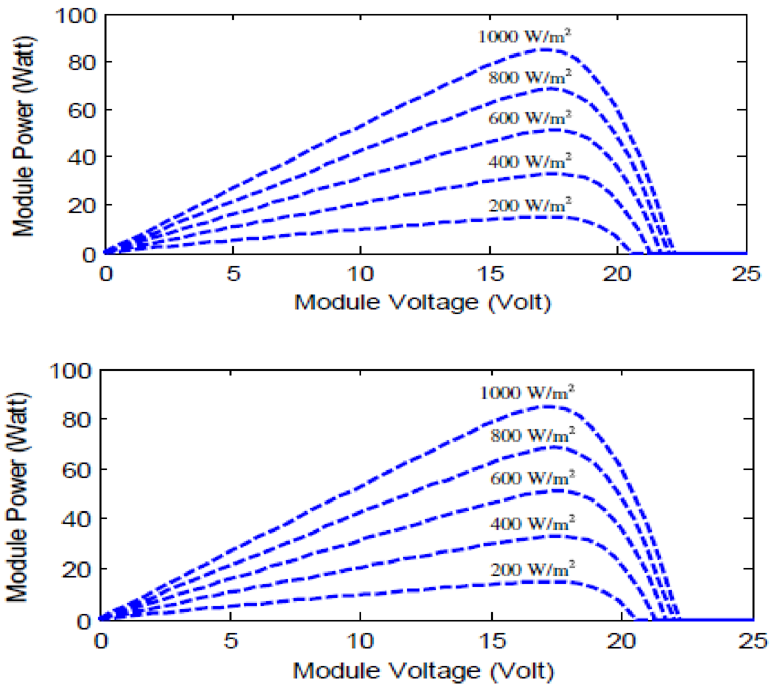

Fig. 5. PeV and IeV characteristic curves of a PV module.

4.Simulations and Discussions Performance of FFC Based Wind-Storage and PV Systems

The improvement in under-frequency response using FFC based wind-storage system can be demonstrated using simulations in four different cases as shown in Table 1.

Table 1 : Different scenarios to investigate the efficacy of FFC based WIND-STORAGE and PV systems

Case 1:	only conventional plants respond to inertial respond
Case 2:	In addition to conventional plants, wind farms respond to the frequency support using wind energy control block
Case 3:	In addition to conventional plants and wind farms, BESS provide frequency using FCC
Case 4:	In addition to conventional plants and PV generators, BESS provide frequency using FCC

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. 6.

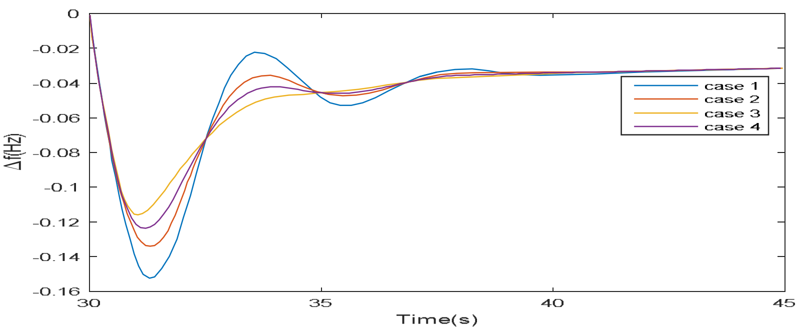

Fig.6. System frequency response for a step load disturbance for Difference cases.

The improvement in RoCoF, which can be observed in case#2/case#3, can be attributed to the power released from wind generators and is enabled through fuzzy-logic based control block. The power sharing among different types of generators is shown in figure. 7.

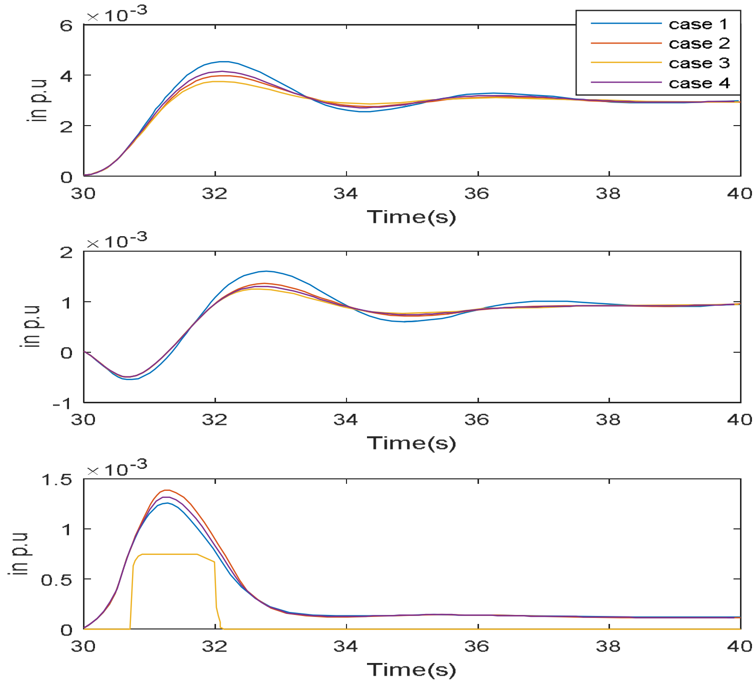

Fig.7. Power sharing for a step load disturbance for different cases.

The effect on frequency response for all cases is investigated in Fig. 8.

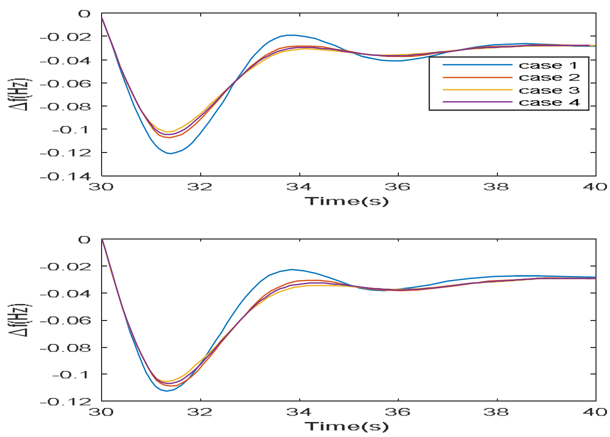

Fig.8. Frequency performance when system lost part of generators.

5.Conclusion

Increasing penetration of non-inertial wind and PV 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 and PV systems.

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