LOAD FREQUENCY CONTROL FOR AN ISOLATED HYBRID POWER SYSTEM WITH HYBRID CONTROL TECHNIQUE AND COMPARATIVE ANALYSIS WITH DIFFERENT CONTROL TECHNIQUES

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DOI: https://doi.org/10.22452/mjcs.sp2020no1.6

ABSTRACT

This paper presents a hybrid isolated power system modeling and Load Frequency Controller (LFC) for different penetration levels of wind power generation. The system considered here consists of a conventional diesel generator, wind generator and energy storage system for a LFC. The purpose of the considered system is to suppress the frequency deviations (balancing the real power generation and demand). An inertia control is used to obtain the best possible gain of the wind system and Fuzzy Logic Control (FLC) is used to control the frequency of the hybrid system. The results are compared with different control techniques. The dynamic performance of the system is studied at different cases by changing the wind penetration level and also by increasing the load disturbances.

Keywords: ***Doubly Fed Induction Generator (DFIG), Renewable Energy Sources (RES), Fuzzy Logic Control (FLC), load frequency control, superconducting magnetic energy storage system, Wind Energy Conversion System (WECS)***

1.0 INTRODUCTION

Due to the geographical conditions, there are many places which are not connected to the grid as many of the islanded places depend on diesel generator. The faster exhaustion of fossil fuels led to utilize RES together with energy storage systems facing a lot of technical challenges[1], which are the alternative power sources for small islanded power systems. The uncertainty in the primary supply is because of the imbalance between randomly change in power output of renewable energy and load demand can lead to more fluctuations in voltage and frequency which leads to system blackouts. This is an existing problem in the research area of power system stability. The power output from the renewable energy is limited to a certain extent due to limitations in frequency of the system. These problems in isolated power system can be solved by providing continuous control over the RES. Due to the uncertainties in the wind speed, the stability of the wind energy system is of more concern, whereas primarily frequency should be maintained stable for which the LFC can be used. The renewable uncertainties are also considered due to the change in generation from the renewable time-to-time which affects the whole system.

The conventional Automatic Generation Control (AGC) is capable of controlling the frequency of the system within the limits of nominal frequency without considering renewable sources, but with 50% of renewable penetration of the same system to reduce half of its nominal value which make AGC to maintaining frequency within the limits[2]. The uncertainty and penetration of wind energy into the system causes the frequency drastically. This problem is resolved using wind generation emulating inertia which leads to extra generation. The load shedding method is implemented to solve this issue[3]. Therefore for this frequency deviation problem in an island power system is more serious, so a constant control on the power supply from the renewable energy sources are required[4].

The conventional controllers like Proportional Integral (PI) controller are extensively used in LFC. Due to its less robustness and limitation to certain parameters, they are not suitable to use at various operating points. For such problem various adaptive control techniques are used for LFC problems. Many researchers have proposed different control techniques for LFC to an island system and tested their dynamics, and coefficient diagram method is implemented to increase the robustness of system with heat pump and electric vehicle[5] and a dynamic dead band control and moving average filter is used in wind power plant model[6].

Different control techniques and schemes are used in frequency control with wind turbine generators as discussed by researches in[7]–[9]. DFIG wind generators are contributed for active power balancing[10]. Fuzzy logic controller is proposed in hybrid wind energy system along with Superconducting Magnetic Energy Storage System (SMES) is proposed in [11].Isolated power system with wind is presented for LFC[12]. The fuzzy-PID controller has been considered for interconnected multi-area system[13]. A quasi optimization technique is proposed for hybrid wind power system[14]. A cluster of nonlinear adaptive algorithms were proposed to control the wind turbines at different speeds[15].An Model Predictive Control (MPC) method is implemented in multi area system consisting wind generation[16].A new control strategy of designing a non linear SMC is proposed for wind generating system used in two area system for balancing the generation and loads[17]. This study gives the wind generation support to load frequency problem with different control strategies, due to intermittent nature a supplementary energy storage system can be used to support the wind energy during the fluctuations.

Recent advancements in technology leads to the use of renewable energy sources in the power system by incorporating the energy storage technology, SMES is one of the energy storage replacing the conventional storage technology. A hybrid power system is designed in which SMES is utilized and tested for stability of the system using Ant Colony optimization[11]. A PWM-VSC convertor control and DC-DC chopper with UJT control technique is presented to suppress the frequency deviations at various atmospheric conditions[18]. In this paper a hybrid control strategy is implemented for an isolated power system using a wind inertial control and a FLC for conventional diesel generator, and also an energy storage system is coordinated with the change in the load and variation of wind power in the system. The control strategy is tested for different load and wind penetration levels in the system.

This paper is arranged in the following as, in section 2 the dynamic employed models of diesel, wind and SMES is described. In section 3 the hybrid LFC control technique is described with its structure. The proposed island hybrid power system is tested by analyzing time domain simulation results for the two cases by not considering with and without the energy storage device at different penetration level of wind energy is presented in section 4. And finally the conclusion of the work is given in section 5.

2.0 DYNAMIC MODELS USED FOR ISLAND POWER SYSTEM

The structure of island power system used consisting of different generating units and an energy storage is shown in Fig. 1.

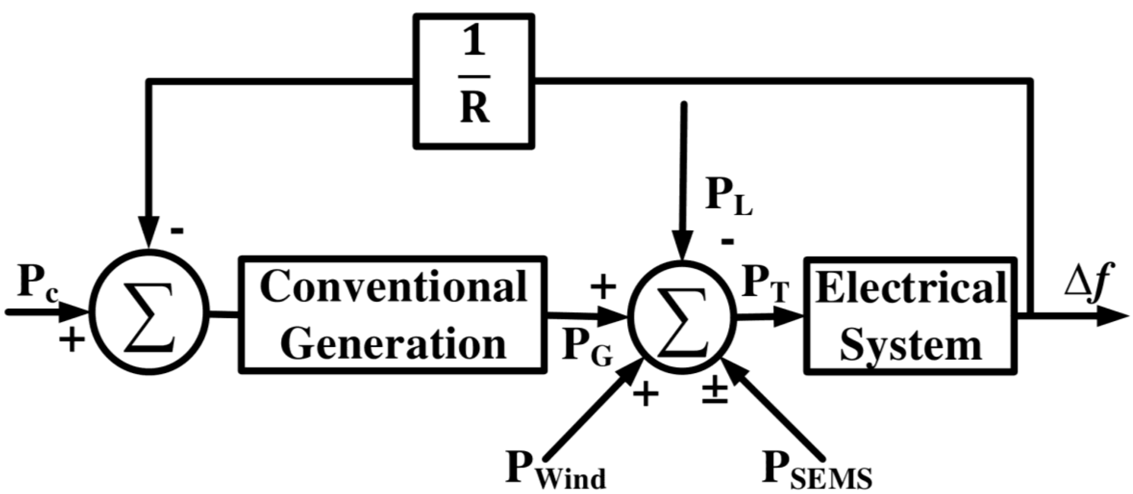

Fig. 1: Basic System Model used for Islanded Power System

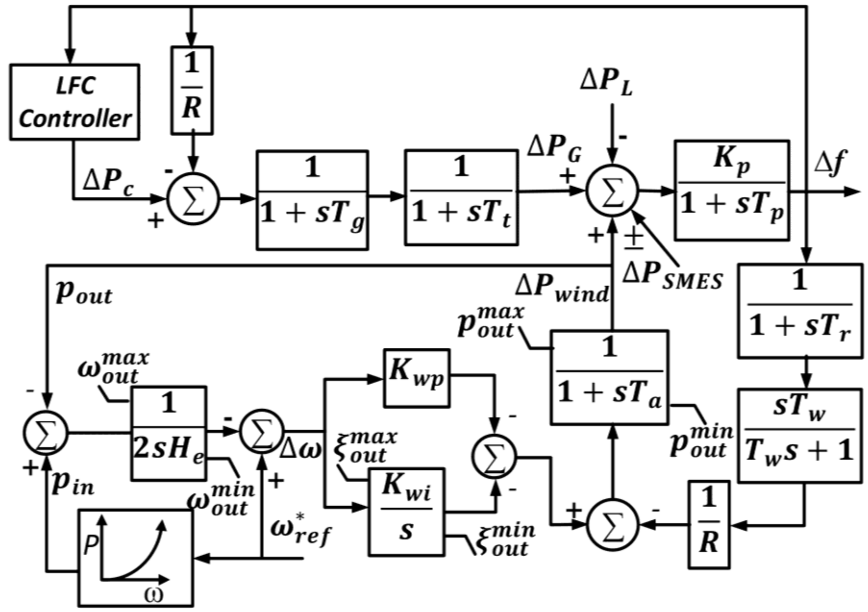

Fig. 2: LFC Dynamic Model with WECS and SMES for the Isolated Power System

The dynamic model of the hybrid power system shown in Fig. 2, which comprises of a conventional generating unit and a non conventional generation source and also includes a storage system for better performance. The test system is developed with a certain limitations in the wind model such way that the fluctuations in the wind can be controlled using the reference conditions. It has two limitations one is speed limier and other one is frequency variation limitation. In this section the models used for this island power system are presented with their block diagrams. The island power system considered composes of three different power generating units a) conventional power system model diesel. b) Wind power system model and c) Energy storage system like SMES etc model as shown in Fig. 2.

The output power generated from conventional generator is PG. The demand power is PL which is subtracted from generated power PG and power generated from wind is added, while energy storage system power depends on change in power disturbances and discharge of storage system. In steady state condition, the total power balance is given by Eqn (1)

$$P_G + P_{Wind} \pm P_{SMES} - P_L = P_T = 0 \qquad (1)$$

2.1 Dynamic Model of Diesel System

In the proposed hybrid system, in place of conventional generator a Diesel Generator (DG) is considered and the model is depicted in the Fig. 3. Due to the fast response and high efficiency in DGs for sudden changes in power generation, the load demand is met due to the changes arising in the demand side[19]. The dynamics of governor and turbine are represented as first-order transfer functions as expressed in Eqn (2) and Eqn (3)

$$\Delta P_T = \left(\frac{1}{1+ST_g}\right)(\Delta P_C - \frac{\Delta F}{R}) \qquad (2)$$

$$\Delta P_G = \left(\frac{1}{1+sT_t}\right)\Delta P_T \qquad (3)$$

where, Tg and Td are the time constants of turbine and governor respectively, R is the droop coefficient of speed regulation, ΔP_T is the change in turbine power, ΔF is the change in frequency.

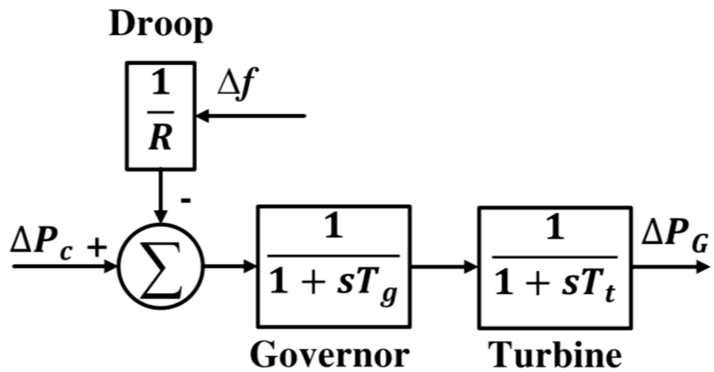

Fig. 3: Diesel Transfer Function Model

2.2 Dynamic Modeling of Wind System

Different types of machines are used for wind energy conversion systems, out of which DFIG and PMSM are popular due to their advantages. One of the best advantage of these machines are both real and reactive power are controlled by operators, even though steady state power is supplied to grid depends on mechanical input received by the wind. The active power is controlled up to certain level by restoring the kinetic energy. This is mainly due to asynchronous speed of the machines that they work. For a LFC system considering wind turbine power generation, when change in load occurs the control strategy mainly is used to change the active power generation from conventional system by keeping wind turbines to generate limited power. This problem is resolved using an inertia control strategy with proportional control technique as used in the traditional units.

The majority of machines used for WECS are variable speed as shown in the Fig. 4 and Fig. 5. These two machines are used to convert mechanical energy to electrical using an electrical link with remaining power system as shown in the Fig. 6. To maintain desired speed (ω_e) power output should be same as the power input i.e., total power loss in the conversion system is nearly equal to zero. This is achieved by restoring the kinetic energy, which is stored into rotational masses, which can be considered for small interval of time to make sure that system is within the operating limits. These machines have the capability to generate power using variable wind speeds and they support for frequency regulation by extracting the stored kinetic energy[20]. In this section, WECS based model for DFIG is used for frequency control. In order to develop a control technique for WECS, we need to consider two important characteristics.

a) Primary power source which cannot be controlled due to wind fluctuations.

b) As mentioned above, WECS can only provide active power fluctuations instantly.

The dynamic model of WECS of DFIG is shown in the Fig. 7. The change in frequency is taken as the reference input to change the power output of the wind generator by varying the speed of the machine.

$$p'_f = \frac{1}{R}\Delta f'_m \quad (4)$$

where, R= droop constant and

$\Delta f'_m$ = the change in frequency measured in island system

The total real power is obtained is given by Eqn(5)

$$p^*_{fw} = p^*_f - p^*_\omega \quad (5)$$

where $p^*_f = -K_{df}\frac{d\Delta f}{dt} - K_{pf}\Delta f$

and $p^*_w = K_p(\omega^*_e - \omega_e) + K_I\int(\omega^*_e - \omega_e)\,dt$

K_{df} and K_{pf} are the constant weighing of derivate change in frequency and weights of change in frequency. K_I and K_P are the constant of PI controller. The parameters used in the island power system are given in Table I. DFIG turbine power characteristics of WECS are considered with respect to different speeds which are shown in Fig. 8. The average wind velocity of wind systems is 12m/s, which is constant.

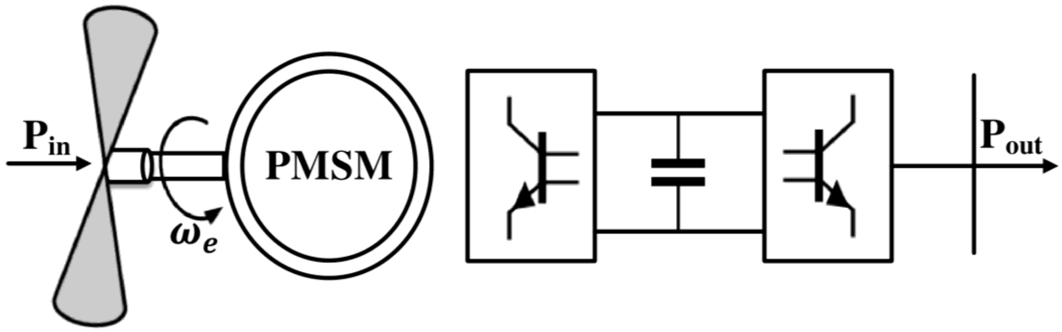

Fig. 4: PMSM Type Wind Turbine

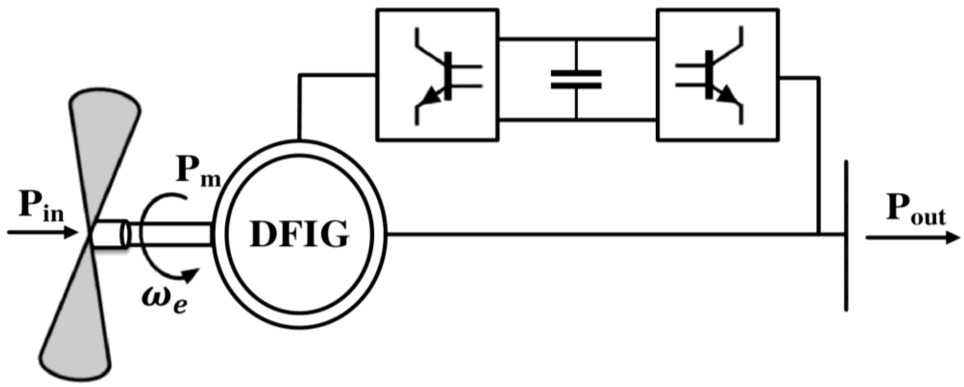

Fig. 5: DFIG Type of Wind Turbine

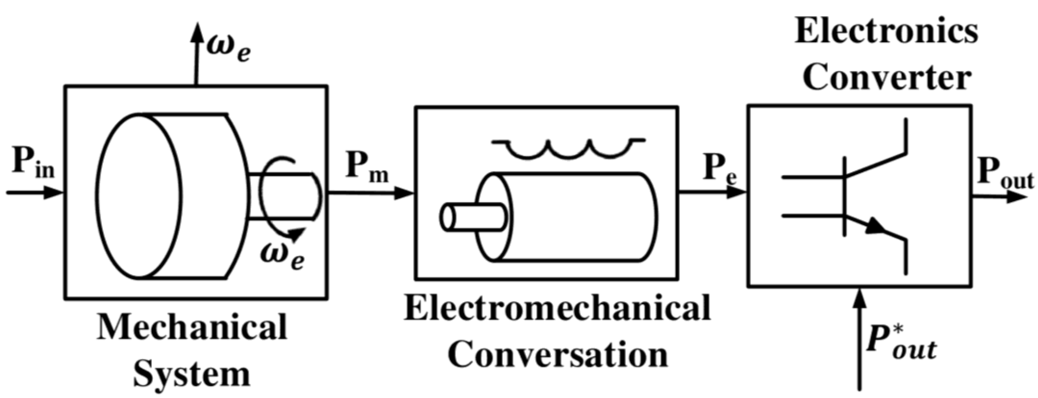

Fig. 6: Equivalent Energy Conversion System

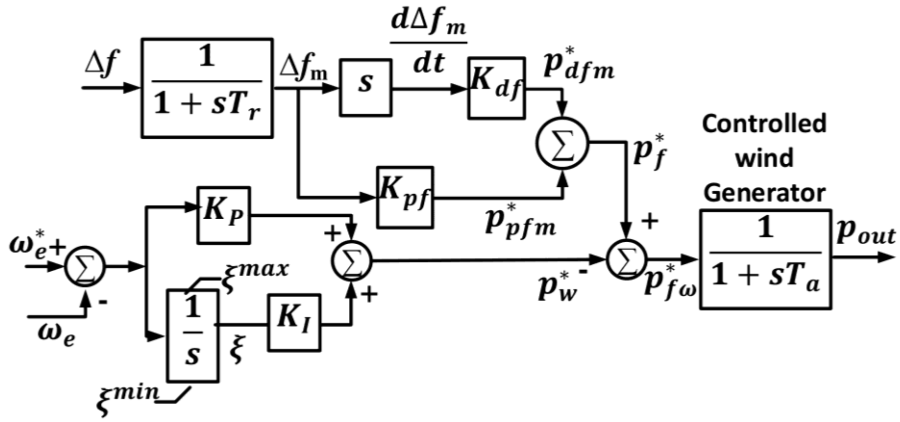

Fig. 7: Dynamic model of DFIG wind generation

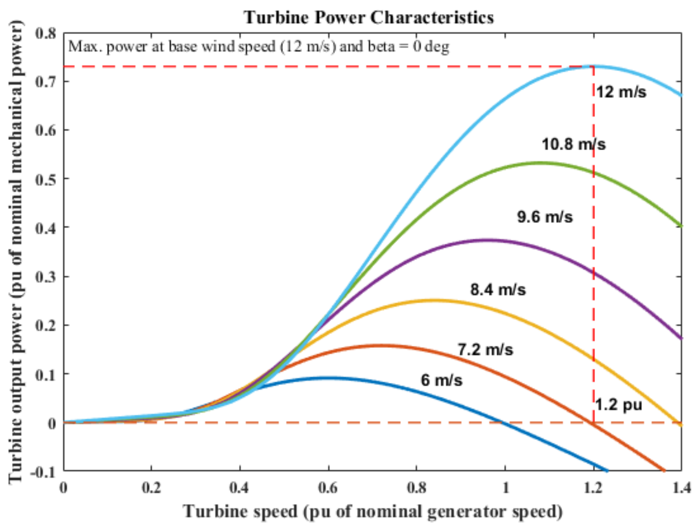

Fig. 8: Turbine Power Characteristics at Different Speeds

2.3 Dynamic Model of SMES

SMES is an energy storage system which stores energy in the form of magnetic field when an electric current is passed through super conductor. The conductor becomes a super conductor when it operates at cryogenic temperature of 20K to 77K, resistive losses doesn't arise. It has a greater efficiency of more than 98%. As shown in the Fig. 9, it consists of a transformer, power conditioning unit, electromagnetic coil and cryogenic system. SMES unit has more advantages like high power and large energy density, response time is quick and low maintenance. Whenever there is a sudden raise in load demand, SMES will instantaneously release energy to compensate from the stored energy through power conversion unit[11].

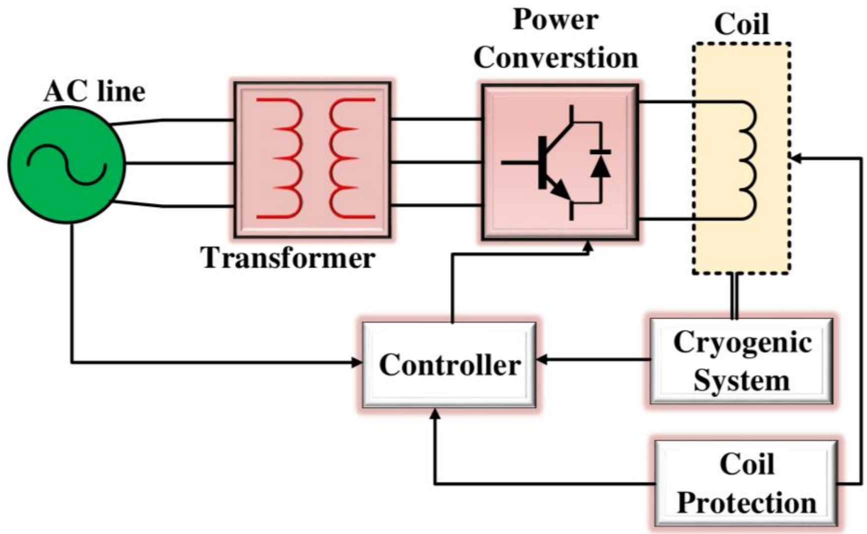

Fig. 9: Basic Schematic Diagram of SMES Energy Storage System

During normal operating conditions of power system, it gets charged from the AC system when the super conducting coil starts charging. The current starts conducting with less electric losses at cryogenic temperature. SMES response faster than the governor control and supplementary control and vice versa. Charging and discharge of SMES unit is controlled through converter by varying the alpha communication angle. If $\alpha<90^0$ converter will act in charging mode, and $\alpha>90^0$ the converter acts in discharge mode. This control of alpha value provides DC voltage across the inductor; it needs to be varied continuously with certain negative and positive values. Without considering the converter and transformer losses the voltage is shown in Eqn(6)

$$E_d = 2V_{d0}cos\alpha - 2I_dR_c \quad (6)$$

where

E_d – Applied DC voltage across the inductor (kV)

V_{d0}- Peak voltage in the bridge circuit (kV)

I_d- current in the inductor coil (kA)

α- firing angle of the converter in degrees

R_c – commutating resistance (ohms)

The transfer function model of SMES is shown in the Fig. 10. The change in coil current is considered as -ve feedback signal to SMES control loop for enhancing current restoration in the coil such that it will be responding for the next load disturbances quickly. Change in DC voltage across the coil and current are given in the equations (7) and (8)

$$\Delta E_D = (-K_{ID}\Delta I_D + K_F\Delta_F)\left(\frac{1}{1+sT_{DC}}\right) \quad (7)$$

$$\Delta I_D = \Delta E_D\left(\frac{1}{sL}\right) \quad (8)$$

where,

ΔE_D - deviation in converter voltage (kV)

ΔI_D – change in coil current (kA)

L – Inductance of the coil (H)

K_{ID} – feedback gain constant of ΔI_D (kV/kA)

K_F – gain constant

The change in real power of the inductor in SMES unit is expressed by Eqn(9)

$$\Delta P_{SMES} = \Delta E_D I_{D0} + \Delta I_D \Delta E_D \quad (9)$$

At any instant of time the stored energy in SMES unit is given by Eqn(10)

$$W_{SMES} = \frac{I_D^2 L}{2} \quad (10)$$

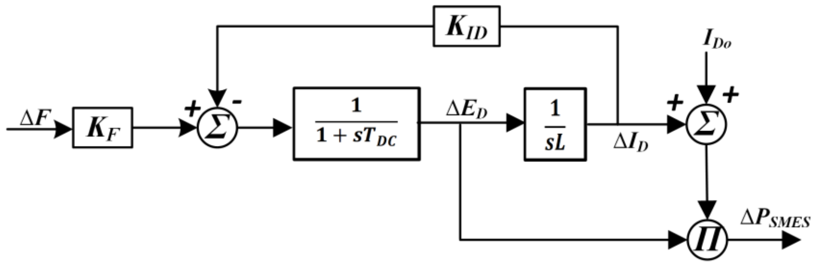

Fig. 10: SMES block diagram

3.0 PROPOSED CONTROL TECHNIQUE

The inertial control technique used in the system is an artificial wind turbine response which will control the power output from wind generation according to the frequency response in the system. The control technique used for frequency variation for DFIG based WECS depends on primary regulation. As stated above, these machines only perform in transient behavior state by using stored kinetic energy. These DFIG machine has advantage of fast response to the frequency regulation, having equal behavior as of the conventional generators. Due to their quick response to frequency support in LFC, it is being considered as shown in Fig. 11. This control strategy has the advantage of fast injection of power from non-conventional generators, to sudden change in load. Such that the conventional generators will not respond to change in loads as quick as possible. One more advantage of this controller is it will not change the non-conventional generators to conventional generators, but it takes advantage of their quick response. The proposed technique depends on the primary regulation in transient condition. The output of the controller is fed as an additional power to the reference of the conventional machine controller.

Temporary system frequency deviation is affordable in nonconventional generators as they can act only in transient manner using the K.E stored in the generator. As a result in equation (4) the frequency term is due to washout filter is shown in Fig 11. It is an inertia control technique which control the wind generation according to the system frequency and wind fluctuation, in Fig 11 there are two feedback loops one is from system frequency and other is form reference speed to power output, based on these inputs the wind power is controlled. As stated above inertia control makes WECS to work as a synchronous generator. For inertia control, a conventional PI controller is utilized to gain the best possible rotor speed after the change in frequency. The total real power is obtained is given by Eqn (11)

$$p_{fw}^{*} = p_{f}^{*} - p_{\omega}^{*} \qquad (11)$$

KI and KP are the constant of PI controller, these are chosen in such that it should have fast recovery of speed and short period of transient speed variation, so that the other conventional generator and energy storage system will be able to inject reactive power needed to balance the power and reduce the frequency deviations. For good performance of generator a recovery time of 20sec is enough. For a frequency change 2-3 sec is needed, for both the conditions PI controller is capable of providing gains. The controller is implemented using MATLAB /Simulink.

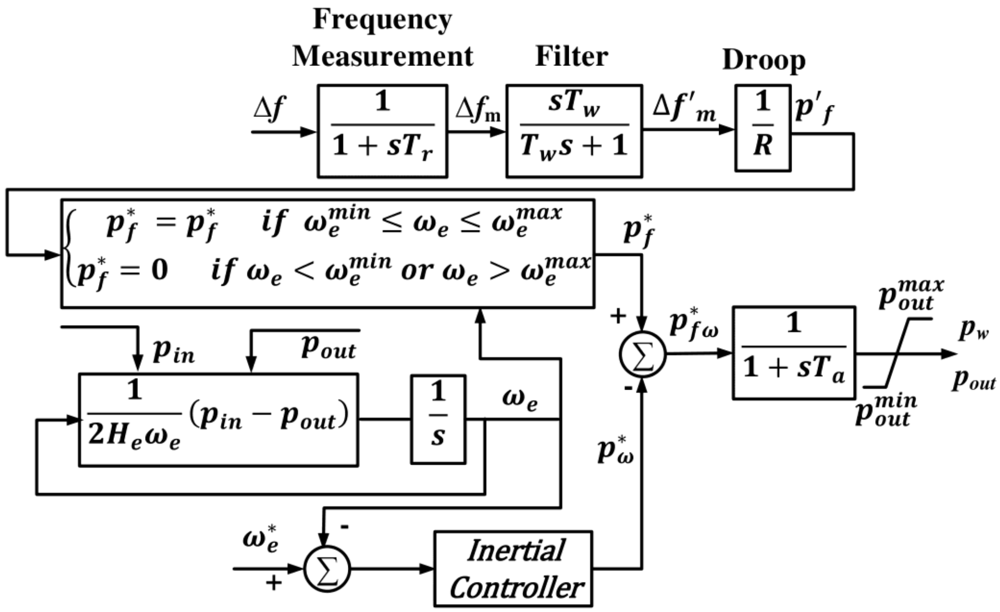

Fig. 11: Inertia Control Technique used for WECS

For conventional generator an intelligent fuzzy PID controller is considered as a LFC controller. In recent times, the FLC is used as an alternative controller to traditional controllers, which manages the processes involving both expertise and traditional controllers. The block diagram of FLC is as shown in the Fig. 12. The FLC has four main blocks, which are fuzzification, fuzzy inference, knowledge base and defuzzification[21] which are explained in detail. To design an FLC selection of control variables suitably are very significant. Commonly, the two inputs for the controller are error and the deviation in error is considered. For selecting the fuzzy parameters such as inputs, membership functions, knowledge based rule and defuzzification there is no definite way. But it is difficult to design a rule base, to find center value of the MFs and its number for FLC. To overcome these difficulties many research works on FLC is presented by various researches in literature survey such as neuro-fuzzy technique[22], FLC-PSO[23], fuzzy self organized control[24], FLC-GA[25] etc. which have the ability to produce a best possible values for controlling the system in a high-dimensional space at high computational cost.

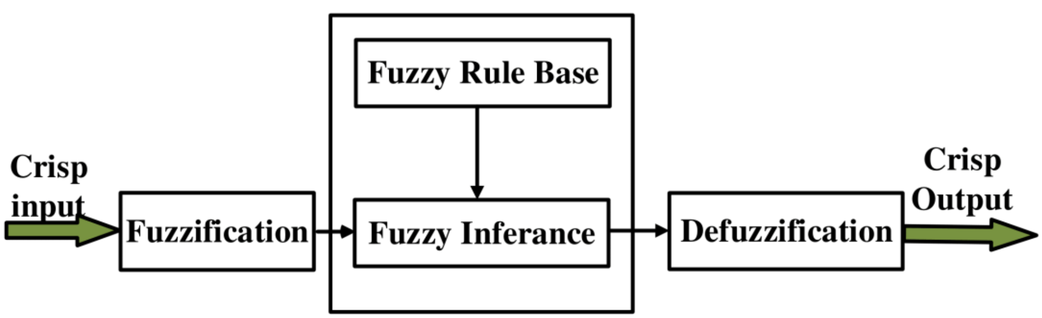

Fig. 12: Block Diagram of FLC

Table I: Rules for Fuzzy Controller

	$\dot{e}$						
e	LN	MN	SN	Z	SP	MP	LP
LN	LN	LN	LN	LN	LN	LN	LN
MN	MN	MN	MN	MN	MN	MN	MN
SN	SN	SN	SN	SN	SN	SN	SN
Z	LN	MN	SN	Z	SP	MP	LP
SP	SP	SP	SP	SP	SP	SP	SP
MP	MP	MP	MP	MP	MP	MP	MP
LP	LP	LP	LP	LP	LP	LP	LP

In this article, FLC is considered for conventional generating unit which has predefined fixed rules which are shown in Table I used for the study and membership function for inputs and output linguistic variables is shown in Fig. 13 and Fig. 14 respectively, which are derived from expert based knowledge. For an effective use of FLC with conventional PI, PD and PID controllers, organization of FLC-PID is shown in the Fig. 15 which is used in the present work.

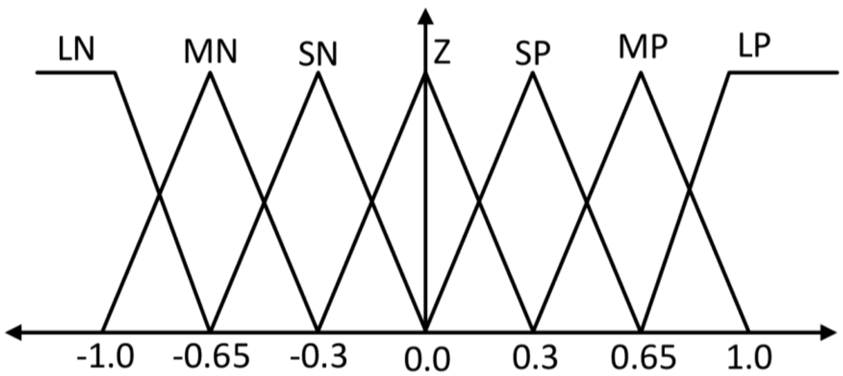

Fig. 13: Membership Function for Input Linguistic Variables

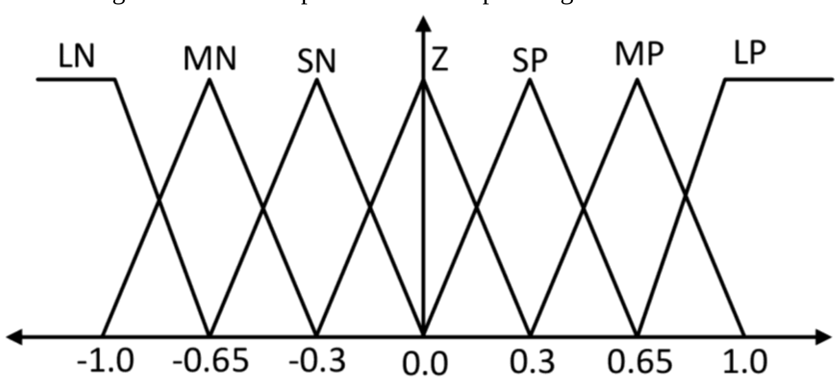

Fig. 14: Membership Function for Output Linguistic Variables

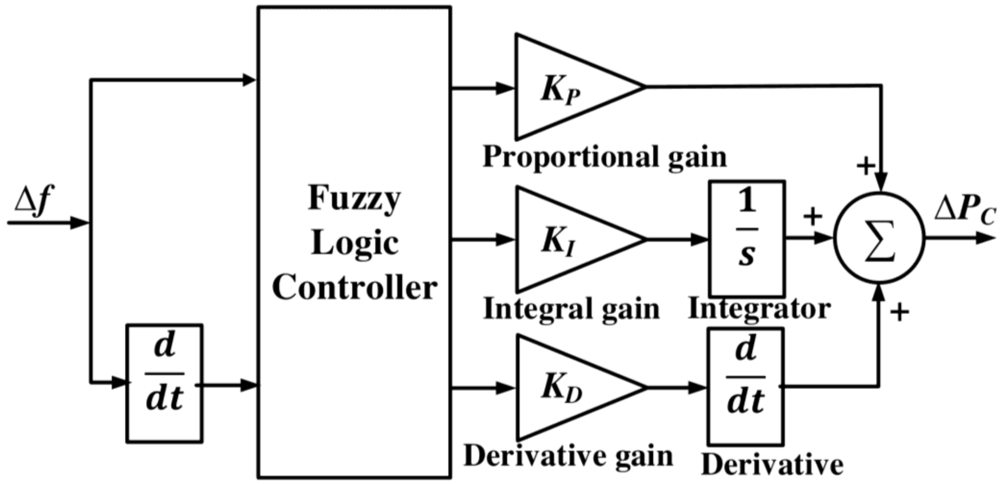

Fig. 15: Proposed Fuzzy-PID Controller

Table II: System Constants Considered for Simulation

Symbol	Description	Value
H_e	WECS Inertia constant	2.4 s
T_w	Time constant for Washout filter	6.0 s
T_t	Time constant of the turbine	1 s
T_g	Time constant of the governor	0.1 s
T_p	Time constant of the power system	10 s
T_A	Controlled WECS time constant	0.2 s
T_R	Time constant of the frequency transducer	0.1 s
K_I	Integral speed constant	0.15
K_P	Proportional speed constant	1.5
$P_{out}^{min}/P_{out}^{max}$	Output power limiters	0.0/1.2pu
$\omega_{out}^{min}/\omega_{out}^{max}$	Equivalent speed limits	0.8/1.2pu
$\xi_{out}^{min}/\xi_{out}^{max}$	Output limits of the Integral controller	-1.0/1.0pu

4.0 RESULT ANALYSIS

The dynamic model for LFC with DFIG-based WECS is considered as the system for testing shown in Fig 2, this system is considered so as to investigate the performance of the control strategy which has been proposed in the previous section. The main aim of this paper is for proposing an efficient LFC scheme with enviable output under the penetration of high wind power. Here by considering the WECS in the power system, along with the energy storage device will help in balancing the load during the sudden disturbances caused by wind fluctuations. But the test system does not include the deviation of wind speed. Here the wind generation is assumed to be supply maximum additional demand as needed by the change in load. Maximum Power Point Tracking (MPPT) system, gives the best speed and allows temporary variation from best speed[26]. To show the performance of the selected LFC method, with different percent of wind penetration with and without energy storage. The parameters used for the island hybrid system is shown in Table II. DFIG WECS parameters are considered in[20]. In Fig. 8 it depicts the power characteristic curves, a constant wind velocity of 12m/s for an aggregated wind system is considered and its penetration level is 50%. The control techniques were implemented using MATLAB/Simulink environment.

In this study, the inertial control and Fuzzy PID controller performances are compared with the conventional control techniques PI and PID. The FLC is designed with a 49 rules and a triangular membership function is employed. The simulation results obtained are shown in the below figures with 5% and 50% wind penetration in the system with a load change (ΔPD) of 10% in both the cases. Fig. 16 and Fig. 17 depicts the better performance of the proposed fuzzy-PID to conventional PI and PID controller respectively. For the same isolated power system by including a energy system, it was observed that dynamics of the system which are greatly improved is shown in the Fig. 18 and Fig. 19. In Table and

Table the wind penetration level along with and without energy storage system performance indices are presented. Maximum peak overshoot as well as settling time of frequency deviation for several control techniques is shown in Table III and IV. We can conclude easily that the transient response is much more smoother in case of system with energy storage system compared to without energy storage. The settling time is less for fuzzy PID controller.

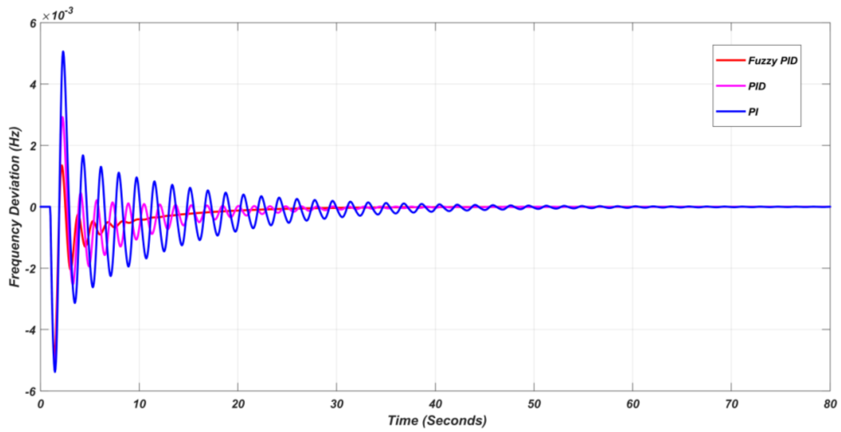

Fig. 16: Frequency Variation of PI, PID Fuzzy-PID in the Isolated Power System for Wind Penetration of 5%

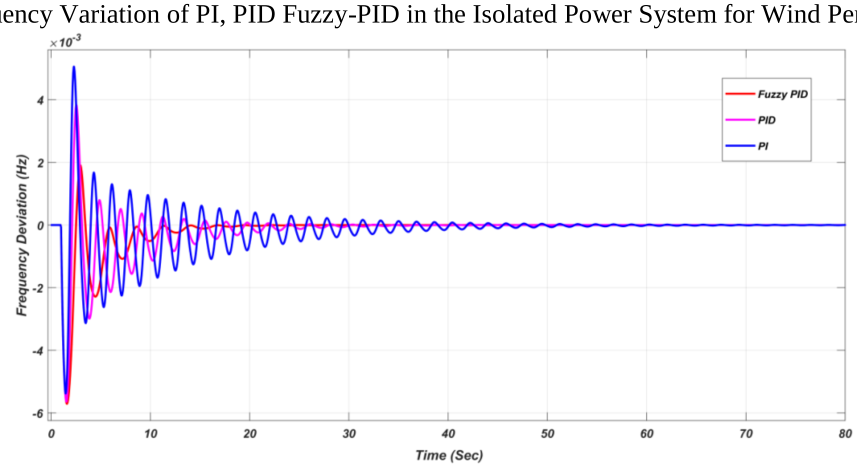

Fig. 17: Frequency Variation of PI, PID Fuzzy-PID in the Isolated Power System for Wind Penetration of 50%

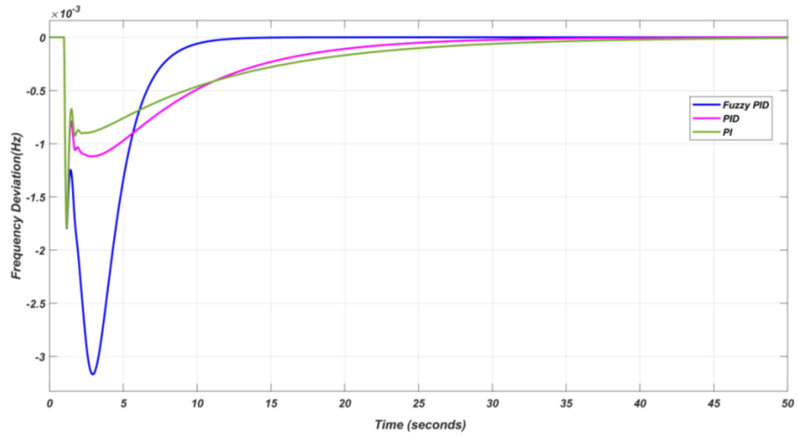

Fig. 18: Frequency Variation of PI, PID Fuzzy-PID in the Isolated Power System with including Energy Storage System for Wind Penetration of 5%

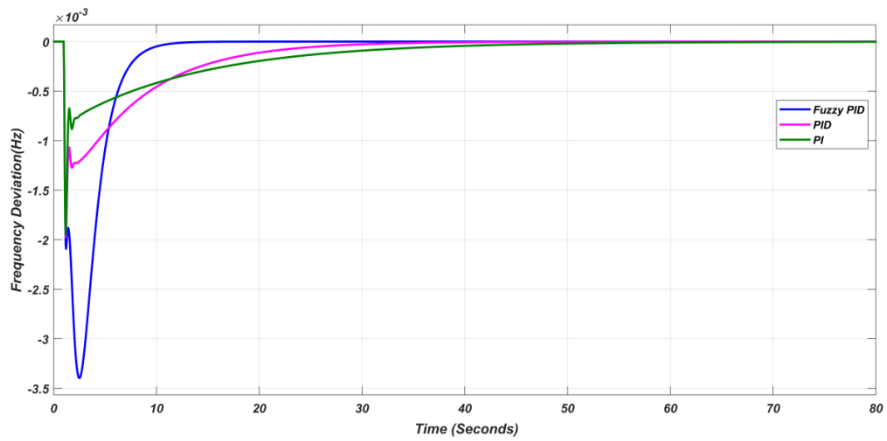

Fig. 19: Frequency Variation of PI, PID Fuzzy-PID in the Isolated Power System with including Energy Storage System for Wind Penetration of 50%

Table III Comparison of Island Power System with Different Wind Penetration level without Energy Storage System

	Settling Time			Maximum Overshoot		
	PI	PID	Fuzzy- PID	PI	PID	Fuzzy- PID
5% wind penetration	72.5	48.68	28.6	0.004089	0.002939	0.001379
50% wind penetration	66.98	37.9	25.15	0.005059	0.003855	0.001835

Table IV Comparison of Island Power System for Different Wind Penetration Level along with Energy Storage System

	Settling Time			Maximum Overshoot		
	PI	PID	Fuzzy- PID	PI	PID	Fuzzy- PID
5% wind penetration	58.6	38.45	15.29	-0.0006737	-0.0007828	-0.00126
50% wind penetration	70.66	47.15	18.49	-0.0006767	-0.001058	-0.001819

5.0 CONCLUSION

This paper concentrates on LFC in island hybrid power system with a wind energy system and an energy storage device causes frequency regulation in conventional system in two ways, one is reduction in total inertia obtained due to the synchronous power conversion and second is, in frequency support. In this article an inertial control is used for this possibility. This method improves the inertia control technique by adding an additional power reference signal, which is given by the primary frequency regulator. The modeling and control technique for DFIG wind and SMES are presented, and an FLC is used for conventional generation. The wind penetration for different levels is tested along with load change of 10%. The system is tested with and without consideration the energy storage system. The simulation results show the performance of control techniques with and without the energy storage system. The FLC has good performance when compared with the conventional PI controller and PID controller, furthermore the damping's of the system is reduced while using energy storage system. This work can be further extended by using AI techniques and optimization for better load frequency problems in simulation test. Furthermore inertial control can be used in the grid connected WECS.

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