Design of Frequency Controller for Wind-Solar-Diesel Hybrid Energy System Including Energy Storage

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Abstract- *In this paper presents design of an intelligent Fuzzy Logic Controller(FLC) for hybrid generation system. The system under study consists of offshore wind turbine generators, solar photo-voltaics, diesel-engine generator, FCs, aqua-electrolyser, FESS, battery energy storage system, ultra capacitors (UC). The fuel cell-aqua electrolyzer combination is used as a backup and a long-term storage system. Ultra capacitor and battery bank are used in the system for short time backup to supply transient power. When there is an unbalance between the power generated and load demand, the system frequency will deviate from its nominal value. To drive the system responses back to their steady state condition, a frequency controller is needed. The Proportional-Integral controller (PI) parameters are obtained by using trial-and-error method to improve the deviation of frequency profiles. Also compared frequency deviation of different hybrid systems are carried through high-voltage direct current(HVDC)link and high voltage alternating current(HVAC)line for different cases of hybrid system combinations with PI controller. The system responses using FESS-UC and FESS-BESS with PI controller has to be compared. For better improvement in frequency deviation Fuzzy logic controller(FLC) is designed to the hybrid systems. It gives good performance in frequency deviation profile compare to conventional PI controller and results are submitted.*

Keywords- renewable energy, hybrid system, energy storage system, frequency deviation

I. INTRODUCTION

Small scale power generation sources like wind, photovoltaic(PV), fuel cells(FC),small hydro etc. are gradually gaining popularities world-wide and replacing conventional power generating technologies in various applications because of the fast depletion of fossil-fuel, air pollution, high transmission losses, high capital investments, global climatic changes and many more problems. In order to overcome these difficulties and tackle the increasing power demand, an alternative power generation in the form of ”distributed generations ” has been considered as feasible solution to above problems. In particular, advances in wind and PV generation technologies have increased their use in wind alone, PV alone configurations. But the power outputs of wind and photovoltaic are unpredictable and fluctuating in nature due to large variations in wind speed and solar radiations. This may lead to unreliable and poor power supply. In order to overcome these difficulties, All the renewable energy resources with energy storage devices like battery, ultra capacitors can be integrated to formulate different hybrid energy systems for a reliable power supply[1]. The hybrid power system with integration of PV with FC offers promising advantages over independent operation[2].Energy storage plays an important role in hybrid energy system for storing and releasing at proper time. The slower response of FC is eliminated by using it with flywheel energy storage system(FESS) or battery energy storage system(BESS) due to its higher energy density[3].Further ultra capacitor as an energy storage device is incorporated to the hybrid system in order to improve the performance of the system. Ultra capacitors are an attractive choice as energy storage elements. Because of their advantages such as high efficiency, fast load response, flexible and modular structure to be used with renewable sources such as wind and photovoltaic[4-6]. Diesel engine generator(DEG) is introduced into the hybrid system as standby source to meet the deficit in power demand[7]. It can be achieve the better control strategy. The remote wind forms can transmit bulk power generation over long distances in two ways either by high-voltage alternating current(HVAC) line or by high- voltage direct current(HVDC) link. The HVAC line is an economic choice for medium-range wind farms with transmission distances less than 50 km [8].Whereas HVDC link is economical for transmission line more than 50 km as the transmission loss is minimum. The presence of HVDC link reduces the required power generation from DEG so that overall cost of generation can be minimized. Further the intermittent characteristics of offshore wind turbine generators and photovoltaic causes mismatch between the total power supply and load demand leading to deviation in system frequency profile. Frequency is an important parameter which must be controlled, otherwise may create instability in the system performances. So to reduce the overshooting and for minimum frequency deviation we replace this conventional controller and fuzzy logic controller. With this new method reduce the peak overshooting and improve the frequency

deviation performance. The rest of the paper organized as follows. Section 2 describes the modeling of various energy resources and storage systems in the first order transfer functions using small signal analysis. Section 3 describes the configuration of the proposed system. Section 4 describes the integration topologies for isolated hybrid systems. Section 5 describes the Results and discussions.
Section 6 describes the conclusion.

II. SYSTEM MODELLING

The various renewable sources are integrated for an effective and reliable power supply during different load conditions. However the sources like wind and PV have inherently random characteristics due to different climatic conditions. Both wind speed and solar radiations have unpredictable features which may reduce the capacity of the energy storage systems. Hence FC may be integrated with such sources along with the energy storage systems such as BESS, FESS to overcome the problems. Prior to the detailed study of the integrated hybrid systems, the modeling and characteristics of the different components are carried out and presented in the subsequent sub-sections. In the present work with the consideration of small disturbances, the system non-linearities have been linearized in order to minimize the complexities in modeling and frequency deviation analysis. As a result in the modeling part, the system non-linearities have not been taken to consider and the systems are simulated in simplified form as linear first order transfer functions[9].

Hybrid power is the combinations between different technologies to produce power. The term hybrid describes a combined power and energy storage system. The proposed system as shown in Fig.3 comprises of wind turbine generator(WTG), FC, DEG, and Aqua-electrolyzer(AE).The AE is employed to convert the excess part of generated energy from the WTG in to hydrogen to offer the fuel for FCs. The generated wind power from the WTG is given to HVDC link.Net power(P_T) is determined from sum of powers from HVDC link, PV system, Diesel Engine Generator, Fuel Cell Generator, and negative input power to Aqua Electrolyzer. Net power is added to negative sign of FESS and BESS or UC. These energy storage systems store energy during the surplus generation and release efficiently during the peak load demand. The total power generation(P_H) is balanced to total power demand(P_L).The resultant power is given to the load.

2.1 Wind power generation

2.1.1.Large band modeling of wind speed

In this hybrid distributed generation system, the Van der hoven model[10] is considered as a reference model for the wind speed.

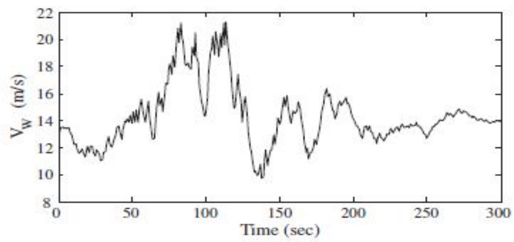

Fig.1 Van der hoven model based simulation of large band wind speed for a time of 300 s[10].

2.1.2.Wind power

The generated power of the wind turbine generator(WTG) depends upon the wind speed V_W.The wind speed is considered to be the algebraic sum of base wind speed(V_{WB}),gust wind

speed(V_{WG}),ramp wind speed(V_{WR}) and noise wind speed(V_{WN}) [11]. Hence wind speed is given by

$$V_W = V_{WB} + V_{WG} + V_{WR} + V_{WN} \quad (1)$$

The mechanical power output of the wind turbine expresses as

$$P_W = \frac{1}{2}\rho A_r C_p V_W^3 \quad (2)$$

where ρ-is the air density(kg/m^3),A_r-is the swept area of blade(m^2) and C_p-is the power co-efficient which is a function of tip speed ratio(λ) and blade pitch angle(β).
The transfer function of WTGs is given by a simple linear first order lag by neglecting all the non-linearities

$$G_{WTG_k}(s) = \frac{K_{WTG}}{1+sT_{WTG}} = \frac{\Delta P_{WTG_k}}{\Delta P_W} \quad (3)$$

For *k*=1,2 and with K_{WTG}-the gain constant and T_{WTG}-the time constant.

2.2 Photovoltaic(PV) power generation

A PV system consists of many cells connected in series and parallel to provide the desired voltage and current. The voltage and current relationship is non-linear in nature. The maximum power output of the PV array varies according to solar radiation or load current. Therefore control strategy is required to use solar radiation effectively in order to obtain maximum power.

The output of the PV system can be expressed as

$$P_{PVPG} = \eta S\emptyset[1 - 0.005(T_a+25)] \quad (4)$$

where η- is the conversion efficiency of the PV array,S-the measured area of the PV array(m^2), $\emptyset$-is the solar radiation(kw/m^2) and T_a-is the ambient temperature($^\circ C$).
The transfer function of PV can be given by simple linear first order lag

$$G_{PV}(s) = \frac{K_{PV}}{1+sT_{PV}} = \frac{\Delta P_{PVPG}}{\Delta\emptyset} \quad (5)$$

where K_{PV}-the gain constant and T_{PV}-the time constant.

2.3 Fuel-cell(FC) power generation

Fuel cells are static energy conversion device which converts the chemical energy of fuel(hydrogen)directly into electrical energy. They are considered to be an important resource in hybrid distributed power system due to the advantages like high efficiency, low pollution etc. Neglecting all the non-linearities, transfer function of FC can be given by a simple linear first order lag

$$G_{FC}(s) = \frac{K_{FC}}{1+sT_{FC}} = \frac{\Delta P_{FC}}{\Delta f} \quad (6)$$

where K_{FC}-gain constant and T_{FC}-is time constant

2.4 Diesel engine power generation

Standby diesel engine generator(DEG) work autonomously to supply the deficit power to the hybrid system to meet the supply-load demand balance condition.

The transfer function of DEG can be given by a simple linear first order lag

$$G_{DEG}(s) = \frac{K_{DEG}}{1+ST_{DEG}} = \frac{\Delta P_{DEG}}{\Delta f} \quad (7)$$

where K_{DEG}-is the gain constant and T_{DEG}-is the time constant.
2.5 Aqua-electrolyzer(AE) for production of hydrozen

A part of P_{WPG} or/and P_{PV} is to be utilised by AE for the production of hydrogen to be used in fuel-cell for generation of power.

The transfer function can be expressed as first order lag

$$G_{AE}(S) = \frac{K_{AE}}{1+ST_{AE}} \quad (8)$$

where K_{AE}-is the gain constant and T_{AE}-is the time constant.

2.6 FESS/BESS as energy storage system

Flywheel energy storage system(FESS) or electromechanical battery. It is kinetic energy storage device and behaves like batteries.

The transfer function of the FESS can be represented as first order lag

$$G_{FESS}(s) = \frac{K_{FESS}}{1+ST_{FESS}} = \frac{\Delta P_{FESS}}{\Delta f} \quad (9)$$

where K_{FESS}-is gain constant and T_{FESS}-is time constant.

Battery energy storage system(BESS) is mainly used for load levelling, harmonic cancellation and voltage control. It could also be utilised to provide additional damping to power system swings to improve both transient and dynamic stability. The BESS can provide rapid change of active and reactive power both in positive and negative value. The ability to quickly change the operation of the BESS from a load to a generator. It means the BESS can be modulated to oppose any frequency oscillation in the power system.

The transfer function of BESS can be represented as first order lag

$$G_{BESS}(s) = \frac{K_{BESS}}{1+ST_{BESS}} = \frac{\Delta P_{BESS}}{\Delta f} \quad (10)$$

2.7 Ultracapacitors as alternative energy storage device

Ultracapacitors(UC)are electromechanical type capacitors. It has fast charge-discharge capability, longer life, no maintenance and environmental friendliness. UCs are used to store electrical energy during surplus generation and deliver high power within a short duration of time during peak-load demand[12]

The transfer function of the ultracapacitors can be represented as a first-order lag

$$G_{UC}(S) = \frac{K_{UC}}{1+ST_{UC}} = \frac{\Delta P_{UC}}{\Delta f} \quad (11)$$

where K_{UC} is the gain constant and T_{UC} is the time constant of the ultracapacitor bank.

2.8 Controllers

a. PI controller

Proportional-integral(PI) controllers are used before the AE, FC and DEG to minimize the mismatch in supply and power demand. Hence the deviation in frequency profiles in presence of storage system combinations.

The transfer function of PI controller can be expressed as

$$G_{PI}(s) = K_P(1 + \frac{1}{T_i S}) \quad (12)$$

where K_P is the proportional gain and T_i is the integral gain.

The input of each controller installed before AE,FC and DEG is the error in supply demand ΔP_sAnd the product of frequency deviation of the power system and the gain $k\Delta f$.The reason for multiplying Δf with a gain constant *k* is that the frequency deviation Δf is very small as compared to the deviation in supply ΔP_s.The gain constant *k* values are taken on the basis of trial-and-error method[13]. Then the supply error and the deviation in frequency of the power system is small. The value of the gain constant of aqua-electrolyzer(k_{ae}),fuel cell(k_{fc}) and diesel generator(k_{deg}) are taken 50, 10, 40 respectively.

The optimal parameters of the PI controllers are determined based on trial-and-error method. Then the error in supply Demand ΔP_s is minimum. By controlling ΔP_s and Δf we can supply high quality power to the connected load.

b. Fuzzy logic controller(FLC)

Fuzzy logic Controller having capability that handling the problem with imperfect knowledge and it acts as effective alternative. A fuzzy logic controller has been introduced for minimizing the frequency deviation in the hybrid distributed generation system. It gives several advantages like less overshooting and better performance and simple design. In this controller generally does not need the information of complete model, but it pre requisite the model[14]. The fuzzy logic controller has two inputs and one output as shown in fig.2.

The two FLC variable inputs are error *e*, and change in error Δe defined by

$$e(k) = P_{Lref}(k) - P_L(k) \quad (12)$$
$$\Delta e(k) = e(k) - e(k-1) \quad (13)$$

The FLC output is the change in control variable$\Delta u(k)$ and it is added to the previous control variable *u(k*-1) to give the current control variable *u(k).*

$$u(k) = \Delta u(k) + u(k-1) \quad (14)$$

where *k* is sampling time. The design of the considered FLC is primary based on trial and error procedure to the hybrid energy system. The fuzzy logic sets divides the input variable (error E) into five fuzzy sets NL (negative low),NM(negative medium), P (zero), PB (positive big), PM(positive medium), the second input variables also divided into the above mentioned 5 types. The fuzzy inference is carried out by using mamdani's method. The output is calculated by using diffuzifier block. The centroide method is used for this diffuzifier block to determine the output of this Fuzzy Logic Controller. The output is change in control variable which uses the base rule of Table1.

Table 1. Rule Base of Fuzzy Logic Controller[14].

E/CE	NL	NM	P	PB	PM
NL	PB	PB	P	NL	NM
NM	PB	PB	PM	NM	P
P	NM	NM	NM	NM	NM
PB	NL	NL	P	PM	NL
PM	NM	P	NM	NL	NM

For example, assume that M rules in the fuzzy system, where the $_{i}{}^{th}$ rule has the fallowing form:

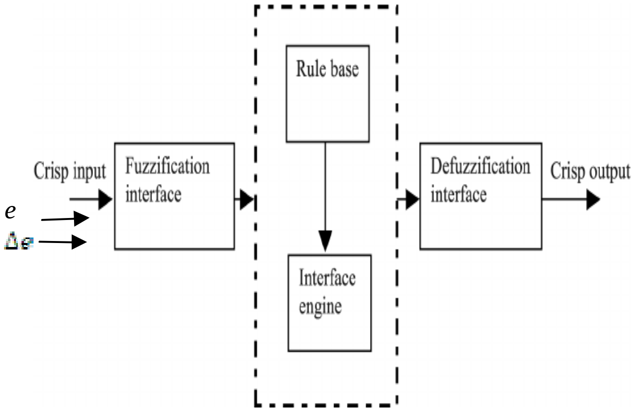

Fig.2.Structure of Fuzzy Logic Controller[15]

III. CONFIGURATION OF ENERGY RESOURCES/STORAGE SYSTEMS

The various energy resources/storage systems may be integrated to form hybrid system as shown in Fig.2. In this analysis power is generated through three WTG, PV,FC, DEG and AE as shown converts a part of generated power from wind or/and PV for hydrogen production to be used by fuel cells.

The total power generation from the hybrid system is given as

$$P_H = P_T + P_{DEG} + P_{FCPG} \pm P_{FESS} \pm (P_{BESS} or P_{UC}) \quad (15)$$

Where

$$P_T = P_{WPG} - P_{AE} = (\sum_{i=1}^{2} P_{WTG_i} \; or/and \; P_{PVPG}) - P_{AE} \quad (16)$$

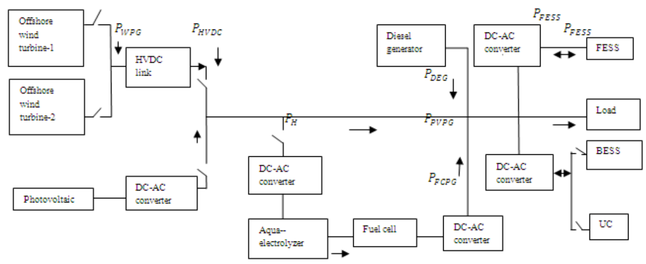

Fig.3. Configuration of hybrid energy/storage system[1]

P_T is the net power of WTGs and PVs fed to the system.

The power-frequency balance is maintained by a proper control of different power generation by the components.

The power balance equation is expressed by

$$\Delta P_e = P_H - P_L \quad (17)$$

P_H is the total power generation and P_L is the total power demand.

The change in the frequency profile(Δf) is expressed by

$$\Delta f = \frac{\Delta P_e}{K_{SYS}} \quad (18)$$

K_{SYS} is the system frequency characteristic constant of the hybrid system. The transfer function for the system variation to per unit deviation is expressed by

$$G_{SYS} = \frac{\Delta f}{\Delta P_e} = \frac{1}{K_{SYS}(1+sT_{SYS})} = \frac{1}{D+Ms} \quad (19)$$

where M and D are equivalent inertia constant and damping constant of the hybrid system[16].

IV. INTEGRATION TOPOLOGIES FOR ISOLATED HYBRID SYSTEMS

In distributed generation(DG) the different energy resources need to be connected to form hybrid system for security. In this analysis three integration topologies along with energy storage systems. Three hybrid systems consists of power generating sources such as offshore WTGs, PV, FC and DEG with the energy storage system combinations are FESS-BESS or FESS-UC. The components of the hybrid systems are properly operated with the help of power converters to meet the power balance condition and for the analysis of variation in frequency deviation profile.

4.1.Hybrid system1(HS1)

In this case consider two offshore WTGs connected together

to generate wind power P_{WPG} in the system. When HVDC link is considered to transmit the wind power generation, the DC power output is converted to AC power P_{HVDC} by suitable converter and is fed to the load. The total wind power P_{WPG} or P_{HVDC} is utilized in the aqua-electrolyzer to produce hydrogen as a fuel for the FC. The FC generates DC power which is converted to AC power P_{FCPG} through DC-AC converter.P_{FCPG} is combined with DEG output P_{DEG} and P_{WPG} or P_{HVDC} representing the average power supply to the connected loads. The surplus(insufficient) power of the considered hybrid system is conveniently stored stored in(released from)energy storage elements with combinations of FESS-BESS or FESS-UC through associated power converters .The resultant power generation can be expressed as

$$P_H = (P_{WPG}\ or\ P_{HVDC}) + P_{DEG} + P_{FCPG} - P_{AE} \pm P_{FESS} \pm (P_{BESS}\ or\ P_{UC}) \quad (20)$$

Table.2 Components of the hybrid systems

Topology	Energy resources/storage elements
HS1	2-WTG+1-AE+1-FC+1-DEG+1-FESS+1-BESS/UC
HS2	2-WTG+1-DEG+1-FESS+1-BESS/UC
HS3	2-WTG+1-AE+1-FC+1-DEG+1-PV+1-FESS+1-BESS/UC

4.2Hybrid system2

In this hybrid system consider two offshore WTGs remain connected to the system while AE and FC are removed from the system. The surplus(insufficient)power of the analysed hybrid system is stored in(released from) FESS and BESS/UC. The resultant power absorbed by the connected load can be expressed as

$$P_H = (P_{WPG}\ or\ P_{HVDC}) + P_{DEG} \pm P_{FESS} \pm (P_{BESS}\ or\ P_{UC}) \quad (21)$$

4.3Hybrid system3

In this case considers the combination of offshore WTGs and PV to the system along with AE and FC remain connected to the system. The total power generation by offshore wind or HVDC link output is combined with the power output of PV system, i.e P_{PVPG}.In this analysis power generation is more due to presence of all energy resources. The resultant power generation can be expressed as

$$P_H = (P_{WPG}\ or\ P_{HVDC}) + P_{PVPG} + P_{DEG} + P_{FCPG} - P_{AE} \pm P_{FESS} \pm (P_{BESS}\ or\ P_{UC}) \quad (22)$$

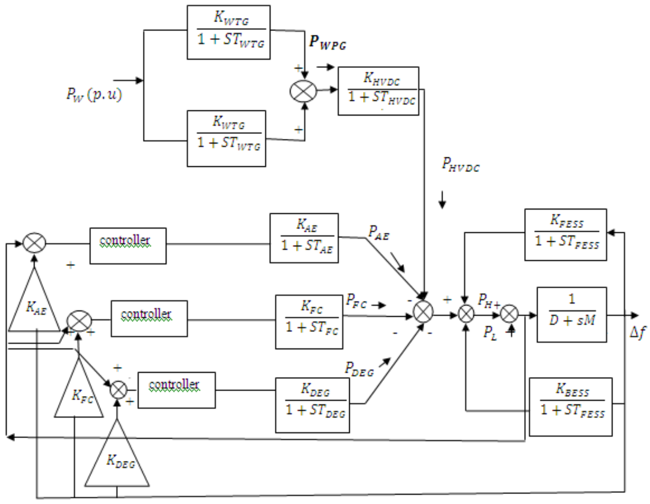

Fig.4.Block diagram for isolated hybrid system

V. RESULTS AND DISCUSSIONS

The hybrid systems with combination of energy storage elements like FESS-BESS and FESS-UC is simulated for the analyse frequency deviations under various operating conditions and disturbances. The parameters of the elements in the hybrid systems are given in Table 1A in appendix and PI controller values in Table 1B.All quantities are in per unit(p.u) values except wind speed V_W is in m/s due to random variation in wind speed. V_W is varied in a large band from 9 m/s to 21 m/s. It is generated for a time period of 300 s and the different cases of isolated hybrid systems are simulated for deviation in frequency profile during that period to know the system performances and behaviour.

The wind speed is 7.5 m/s during 0<t<200 s, suddenly decreased to 4.5 m/s at t=200 s and remains constant at the same value till t=250 s, suddenly increased to 15 m/s at t=250 s and remain at same value till t=300 s. similarly under normal operating conditions, the load demand is taken to be 1.0 p.u. decreased to 0.5 p.u. at t=50 s, remains same up to t=100 s, maintained constant till t=300 s for HS1[17] The simulation result presented in Fig.5. Due sudden raise and sudden fall in the load (P_L) and random variation in wind speed(V_W) the simulation result gives reflect the significant improvement in the deviation in the frequency profile with the incorporation of the UC as comparison to that of BESS when used in combination with FESS.

5.1 Presence of HVAC link to HS1,HS2 and HS3 with PI controller

The large band variation of wind speed is decreasing randomly from 13m/s to 11m/s during the interval of 0-25 s and then increase up to 15m/s during 25 to 50 s, increases randomly from 15m/s to 21m/s and then decreases to 14 m/s during the time interval 50-100 s, randomly increasing from about 14 m/s to 21 m/s and then decreasing to about 11 m/s during the time interval 100-150 s, increasing from 13 m/s to 16 m/s decreasing to around 11 m/s and then increasing to near about 17m/s during the time interval 150-200 s, oscillates around the wind speed 13m/s during 200-250 s and finally vary randomly between 13m/s and 15m/s during the time interval 250-300 s. The variation of wind speed during 0-300 s is shown in Fig.1.The load demand is assumed to constant at 1.0 p.u. for 0<t<50 s, decreased suddenly at t=50 s and remain constant at 0.5 p.u. for 50<t<100 s and increased suddenly to 1.0 p.u. at t=100 s and assumed constant at 1.0 p.u. for 100<t<300 s.

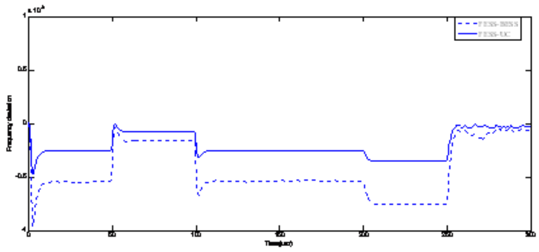

Fig.5.Comparision of frequency deviation in presence of FESS-BESS and FESS-UC storage combinations

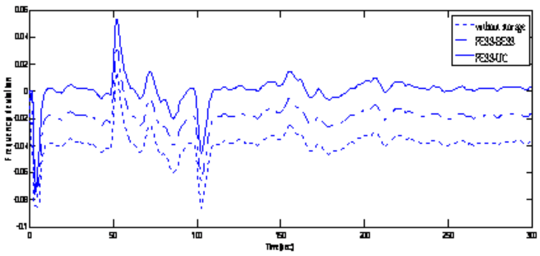

Fig.6.Simulation result of isolated HS1 with HVAC link and PI controller

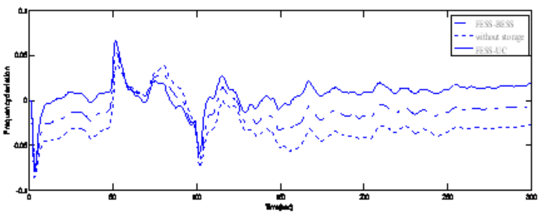

Fig.7.Simulation results of frequency deviation of HS2 with HVAC link and PI controller

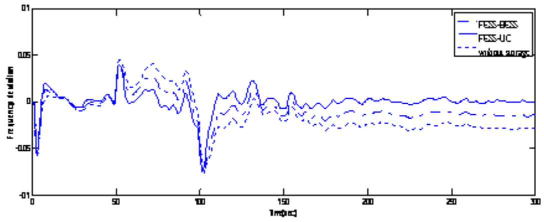

Fig.8.Simulation results of frequency deviation of HS3 with HVAC link and PI controller

The load demand is met by offshore wind turbine generators, fuel cells and the deficit power required is supplied by the diesel engine generator. Aqua electrolyzer uses some portion of the wind turbine generator power output and produces hydrogen fuel for fuel cells. The deviation in frequency of HS1 for different combinations of storage elements FESS-BESS, FESS-UC and without storage elements is presented in Fig.6 to Fig.8

In this three hybrid systems sudden decrease and increase of load are applied at t=50 s and t=100 s the deviation in frequency is increasing suddenly at t=50 s and decreasing at t=100 s due to sudden mismatch in supply and load demand and get oscillates .After few seconds the frequency deviation is exhibiting less oscillation and comes back to the steady state by the proper tuning of PI controller. The comparative assessment clearly reflects that frequency deviation is less with use of ultracapacitor under PI controller action in comparison to other storage elements.

5.2 Presence of HVDC link to HS1, HS2 and HS3 with PI controller

The same wind speed and load conditions are applied as presence in 5.1.Then deviation in frequency profiles are presented in Fig.9 to Fig 11.

Due to sudden variation in wind speed and load the frequency deviation profiles in three hybrid systems transmission losses are reduced and get less oscillates compare to HVAC link.

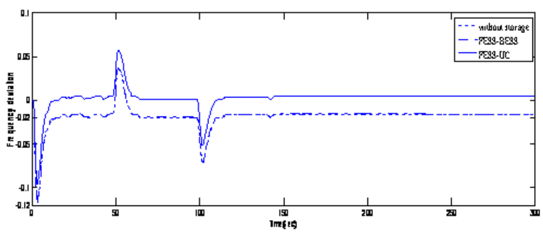

Fig.9.Simulation result of HS1 with HVDC link and with PI controller

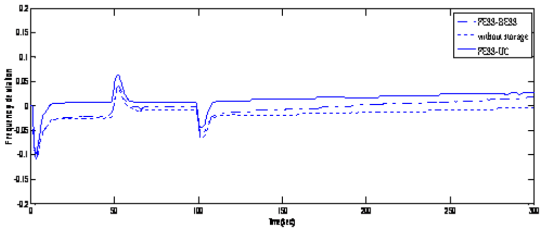

Fig.10.Simulation results of HS2 with HVDC link and With PI controller

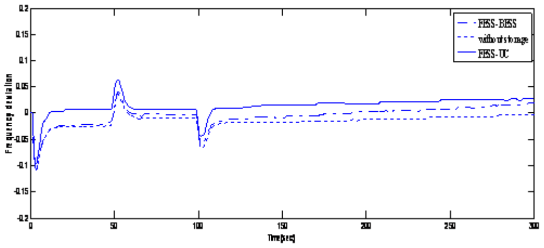

Fig.11.Simulation results of HS3 with HVDC link and with PI controller

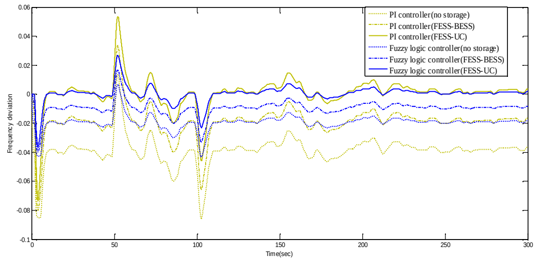

Fig.12.Comparison of HVAC link with PI controller and FLC controller of HS1

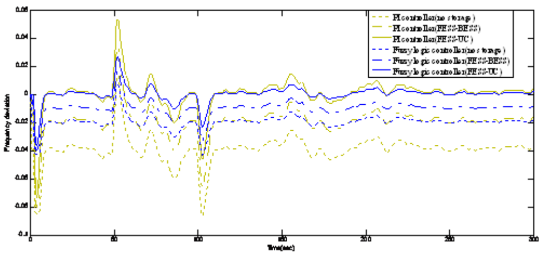

Fig.13.Comparison of HVAC link with PI controller and FLC controller of HS2

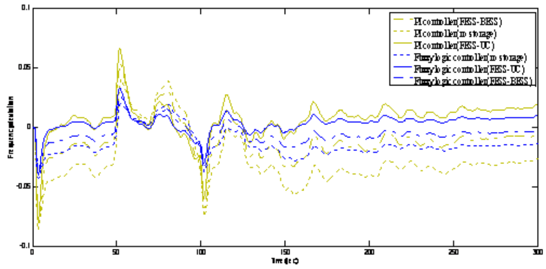

Fig.14.Comparison of HVAC link with PI controller and FLC controller of HS3

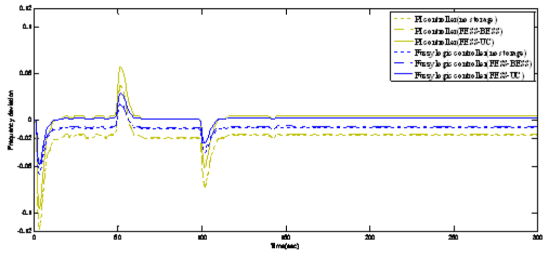

Fig.15.Comparison of HVDC link with PI controller and FLC of HS1

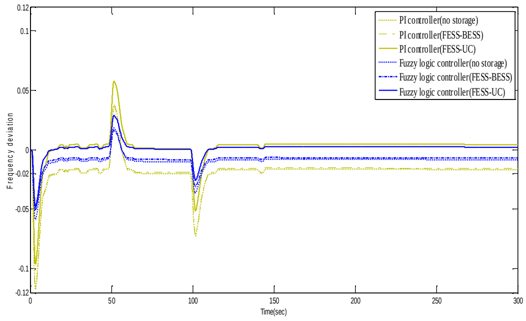

Fig.16.Comparison of HVDC link with PI controller and FLC of HS3

The FLC is to improve the frequency deviation performance under load disturbance conditions. In the proposed FLC, the triangular membership functions is used. They are selected for the input *e(k)*,$\Delta e(k)$ variables and output variable *u(k)*.The peak values of each fuzzy set in the membership functions will influence the overshoot, stability and steady state error of system responses.

The FLC is provides minimum frequency deviation and less overshooting in presence of HVAC and HVDC link in hybrid system. It is clearly determined that by using the fuzzy logic controller in hybrid distributed energy system, we have significant minimum frequency deviation with FLC as shown in Fig.12 to Fig.16.

These results shows the minimum frequency deviation corresponding HVAC and HVDC link. Also compared to isolated hybrid systems with FLC. The FLC gives better performance than the proposed PI controller in hybrid energy system. Also gives better transient and steady state responses and steady state error can be minimized.

VI. CONCLUSION

In this paper minimization of frequency deviation of isolated hybrid distributed generation system elements in presence of HVAC line or HVDC link. A comparative assessment of frequency deviations with different combinations of energy storage with the storage combinations FESS-BESS and FESS-UC and no storage. A significant improvement in frequency is observed from simulation results with HVAC line or HVDC link and incorporation of PI controller for different cases of isolated hybrid system under large band variation in wind speed and load disturbance conditions. It gives minimum frequency deviation and get less oscillations also good steady state response of frequency profile.

To reduce the frequency deviation fuzzy logic controller is introduced instead of PI controller. This fuzzy logic controller gives minimum steady state error, reduce overshooting and also improve overall performance of the hybrid energy system.

APPENDIX

Table 1A

Gain constant(k)	Time constant(T,s)	Other parameters
$K_{WTG} = 1.0$ $K_{AE} = 0.002$ $K_{FC} = 0.01$ $K_{PV} = 1.0$ $K_{FESS} = -0.01$ $K_{BESS} = -0.003$ $K_{UC} = -0.7$ $K_{DEC} = 0.003$ $K_{HVDC} = 0.005$	$T_{WTG} = 1.5$ $T_{AE} = 0.5$ $T_{FC} = 4.0$ $T_{PV} = 1.8$ $T_{FESS} = 0.1$ $T_{BESS} = 0.9$ $T_{UC} = 0.9$ $T_{DEC} = 2.0$ $T_{HVDC} = 0.7$	Inertia constant(M) =0.4and damping constant(D) =0.03

Table 1B

1.Parameters to tune conventional PI controllers for HS1

Energy resources	Proportional gain(K_P)	Integral gain(T_I)
Aqua-electrolyzer	0.01	0.04
Fuel cell	0.05	0.02
Diesel generator	0.03	0.04

2.Parameters to tune conventional PI controllers for HS2

Energy resources	Proportional gain(K_P)	Integral gain(T_I)
Diesel generator	0.03	0.06

3.Parameters to tune conventional PI controllers for HS3

Energy resources	Proportional gain(K_P)	Integral gain(T_I)
Aqua-electrolyzer	0.02	0.03
Fuel cell	0.07	0.01
Diesel generator	0.04	0.08

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