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DISCRETE-TIME MODELING AND CONTROL FOR LFC BASED ON FUZZY TUNED FRACTIONAL-ORDER PD^{M} CONTROLLER IN A SUSTAINABLE HYBRID POWER SYSTEM

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ABSTRACT :
This project investigates the operation of a hybrid power system through a novel fuzzy control scheme. A power system that comprises a photovoltaic (PV), wind energy system (WES), and fuel cell (FC) with a battery energy storage system (BESS), is collectively called a hybrid power system. The research shows discrete-time modeling of fuzzy tuned fractional-order proportional derivative (F-FOPD$^{\mu}$) Controller for load frequency control (LFC) of this hybrid power system. Under varying load conditions, the gains of the fuzzy tuned fractional-order proportional-derivative (F-FOPD$^{\mu}$) will be tuned automatically by a fuzzy logic controller. A diesel generator (DG) with zero-input power is running as a synchronous condenser to provide the reactive power balance and voltage stability to the WES for automatic generation control (AGC). The hybrid scheme is tested under changing system parameters, load fluctuations, and a worst-case scenario which is the occurrence of three-phase symmetrical faults with the opening of circuit breaker (CB) with a delay of 5 cycles. The proposed controller enhances the optimization of the power system as well as decreases the transients. In case of surplus power availability, the secondary load (SL) absorbs the additional power. The control strategy ensures that the error in frequencies remains zero. The proposed scheme of control not only minimizes the frequency oscillation but also attains the minimum steady-state error in case of dynamic load conditions.

Keywords – Photovoltaic (PV), WES, F-FOPD, Secondary load, Fuzzy logic controller.

INTRODUCTION :
Control of interconnected power system considering various aspects has been a topic of intense research in the recent past. Different type of generating units and their effects have been studied e.g. thermal with reheat, generation rate constraint (GRC), reheat and battery energy storage both the areas, hydro turbine and hydro-governor in both the areas, thermal with reheat turbine along with hydro and gas turbine plants in both the areas, etc. Around 70% of the world’s energy is produced by non-renewable sources. Energy generated through these non-renewable resources relies on using them as fuel. Potential energy transformation to electrical energy is carried out by burning these fuels. These soft computing techniques work appropriately for small and simpler systems, however, if used upon a hybrid model having multiple resources, they require complex and costly configuration which has little practical applicability for remote areas where ease of maintenance and cost are on higher priorities. The technique of the distributed control system (DCS) has been used many times before in various research of stand-alone hybrid systems where the excess power is being absorbed by secondary load (SL). Nevertheless, the equilibrium points in this hybrid mesh of renewable energy resources also changes continuously due to the dynamic load conditions and consequently intelligent approaches are being employed. So, instead of using a fixed controller for all the dynamic conditions it is observed that distributed schemes of control are deployed to minimize the cost functions. The discrete-time regulator makes the excess power flow to the SL to maintain the overall hybrid system stability. The regulator senses the change in the frequency of system because of the variation in angular velocity of wind turbine. The change in angular velocity of wind turbine is due to the increase or decrease in consumer loads. The plus point of using this SL

scheme is that it allows the use of relatively cheaper and less complex wind turbine design. Hence for supplying remote areas with cost effective electric power it is an efficient solution. Furthermore, comprehensive plant modelling is not required in this study because of SL consumption is dependent only on the frequency changes that occur due to the load variations. The fuzzy attempts used in F-FOPDμ require the knowledge and experience of the behavior of controller.

The renewable energy power generation and flow varies with the change in climatic conditions. The task is technically very challenging to maintain the frequency of system within the narrow acceptable range. The irregular nature of renewable energy sources also effects the power at the load end, causing a critical problem of power imbalance and frequency fluctuations. Considering the use of asynchronous generator in WES means that the speed variability of wind turbine is limited hence the technique of DCS for LFC is tried on and tested for only an isolated system with dynamic load conditions. The novel technique of discrete time control using F-FOPDμ with SL, for LFC of renewable energy resources (RES) such as WES, PV, fuel cell (FC) with battery energy storage system (BESS), could act as a favorable analysis, which has never been explored previously. This acted as a motivation to extend the existing work even further and apply three-phase fault on the system at the load end with delay of 5 cycles in the operation of circuit breaker. The control supports the desired level of power quality while maintaining permissible limits of both voltage and frequency. The follow up of frequency with change in load must be achieved speedily with negligible oscillations. The purpose of the LFC is to set the smooth power flow at the load end by meeting targets of frequency limits. Hence forth the motivation behind the study in points as:

1) To decrease the fluctuations in frequency which occurred owing to the system disturbances in hybrid system.
2) Discrete-time fractional fuzzy proportional derivative controller is integrated for the hybrid power system. For LFC system performance of PD controller, selftuned fuzzy controller, discrete fractional order PDμ controller is compared with discrete-time fractionalorder fuzzy PDμ controller.
3) To design an efficient discrete frequency control system acting as secondary load controller as well as providing the load frequency control.
4) Fault analysis and transient stability analysis, with circuit breaker operating after 5 cycles delay, are also being carried out.
5) To achieve the IEEE standard 0.5Hz tolerance in frequency for 50Hz power system frequency).

SYSTEM MODELING:

A hybrid energy system containing wind energy system (WES), photovoltaic (PV), fuel cell (FC) and battery energy storage system (BESS) is under consideration. The electrical power generated from these sources is feed to isolated power load. These sources can be installed as a stand-alone and a grid-connected while in stand-alone the batteries are used to store the energy where in grid-connected no batteries are used, and it is directly attached to the grid. The hybrid system has DC side and AC side. The DC hybrid side of the system consists of a PV, FC, BESS, and bidirectional insulated gate bipolar transistor (IGBT) controlled by a 3-phase current-controlled inverter (CCI). The AC side has a discrete frequency controller. Hence, there is not one but two controllers making it a distributed control system (DCS). The CCI having a PI controller maintains the flow of power from the DC to AC side. On the other hand, the discrete frequency control, on AC side, act as secondary controller for LFC. The AC side of the system also includes the WES. The WES contains a wind turbine and an asynchronous generator also known as induction generator (IG), of 250 kW attached with load. It is connected directly without the need of any power electronic devices. The WES is also coupled with a diesel generator (DG) which is operating in Wind Only (WO) mode i.e., the diesel generator is running on zero input. The diesel generator is working as a synchronous machine for voltage regulation. The synchronous machine has the inertia constant H of 1 second and is connected with a voltage exciter for balancing out the voltages of the system. Fig. 1 demonstrates the methodology adopted, to simulate the hybrid system. The Secondary Load (SL) consists of 8-bit 3-phase resistors that is attached in series with gate turn off (GTO) thyristors. The resistors values fed in a binary form of 8-bit value. Fig. 2 shows the internal modelling of SL. The power varies in the range 0 to 255 x PSTEP. The PSTEP is the smallest step. It is the power of least significant bit. In the research PSTEP is equal to 1.4 kW and total power absorbed by the SL is Psec-nom is equal to 357 kW. The SL maximum power (Psec-nom) is twice as greater as the Pload-nom, because of which the hybrid power system is regulated even with zero load. The control signal block uses the reference power PREF sent by discrete frequency regulator, converts into closest 8-bit binary digit (I7-I0) greater than or equal to the last stored result. The 8-bits regulates one 3-phase resistor by switching the related GTO switches. The least significant bit (LSB) I0 controls the smallest resistance of 1.4 kW.

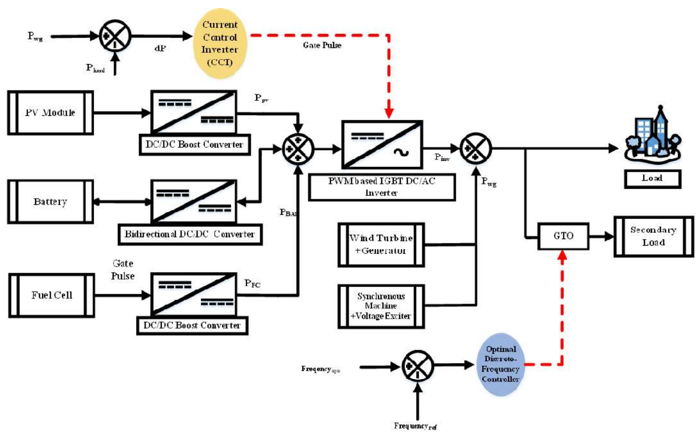

Fig.1. Schematic diagram of hybrid system.

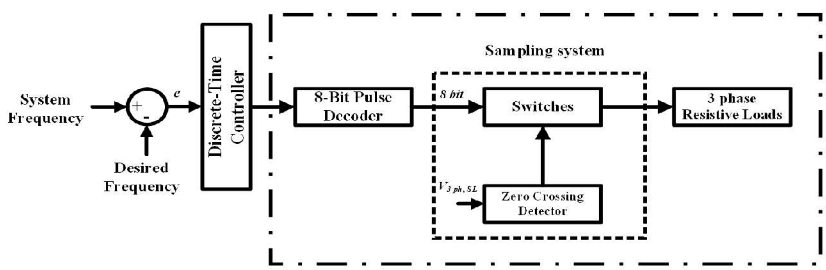

Fig.2. Secondary load (SL) with switches and 3-phase resistors.

Detailed modeling of Current Control Inverter (CCI) shown in Fig. 3. Power reference is transmitted in inverter mode operation, if the difference of $Pabc{-}WT$ minus $Pabcload$, greater than zero the CCI transmits power to the AC side of the system towards the AC load and consume power from PV, FC as well as the BESS. In the rectifier mode operation, difference of $Pabc{-}WT$ minus $Pabcload$ less than equal to zero, the CCI takes power from WES and load side to charge BESS. For the sake of simplicity of the system inverter's reactive power is set to 0, even though it can consumes/produces the reactive power. The IGBTs switching frequency is set as 2.5 kHz and has filter at the output with a 6.85μF capacitor and 2 mH inductor. The inverter is operated in rotating dq co-ordinate. A standard PLL (phase locked loop) with waveform of load voltage delivering the reference for abc-dq and dq-abc coordinate conversions. By adding simple PI controllers active and reactive currents are regulated. Considering all values to be in per unit the voltage value is if close to 1 it is supposed that id-reference is equal to power reference. And iq-reference is equal to zero. The CCI operates on unity power factor. The value of *Kp* is taken 1, and that of *Ki* is considered 200 with a 0.5ms sample time, the response of CCI is robust enough for the load frequency control of the system. Considering the discrete nature of the system SL is consumed in discrete multiple steps of 1.4 kW.

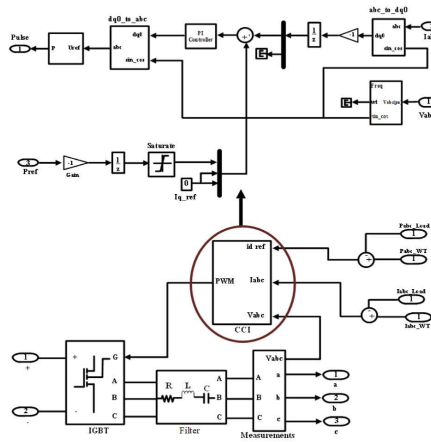

Fig.3. Simulink model of CCI.

FUZZY-LOGIC CONTROL :
Fuzzy control is a method based on set of ''if-then'' statements called the fuzzy rules. These rules make decisions. The rules are designed on the bases of the observations of designer of the controller and the expertise of system operator. The difference of actual frequency of system and reference frequency is the error signal. The error signal and the rate of the change of this error (derivative of the error signal) is the input to the fuzzy controller. The error signal determines how far the frequency of the system is from the desired point, and the rate of change of error signal tells the controller how fast the frequency is changing from the desired set of reference. The fuzzy controller generates an output value, which modulates both KP and KD, hence, changing the system response to better adapt to the situation. The mechanism of fuzzifying to get the output logic is shown in Fig. 4.

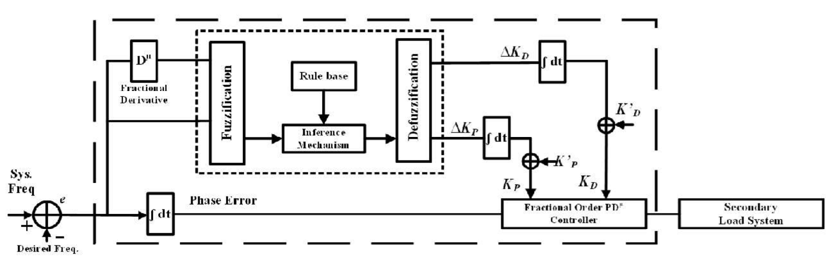

Fig.4. F-FOPDμ controller with fuzzification, inference mechanism and defuzzification.

SIMULATION RESULTS:
Case-1:-
Proposed system:-

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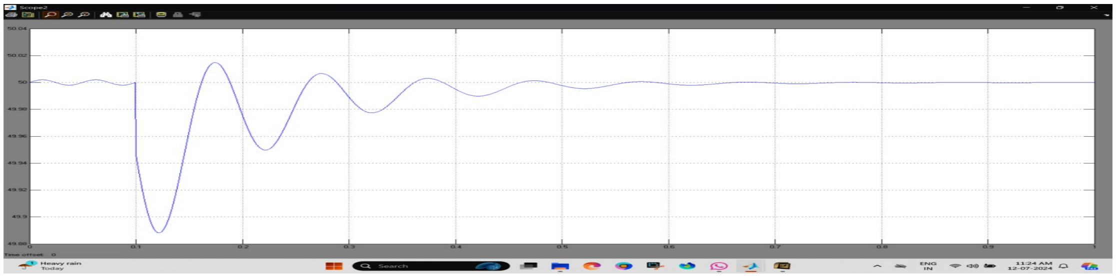

Fig.5. Frequency response FOPD load increment (Fuzzy logic system)

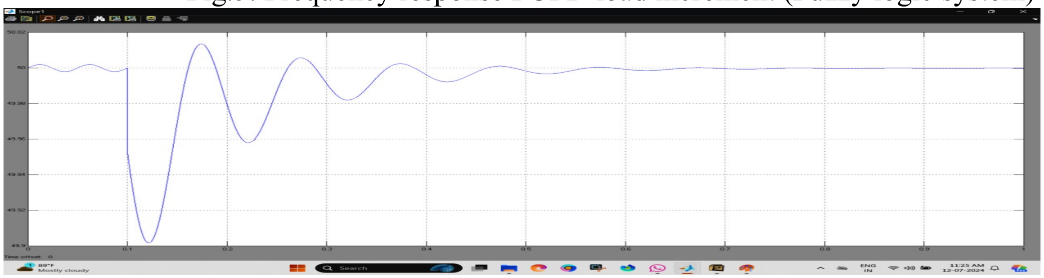

Fig.6 Frequency response F-FOPD load increment (Fuzzy logic system)

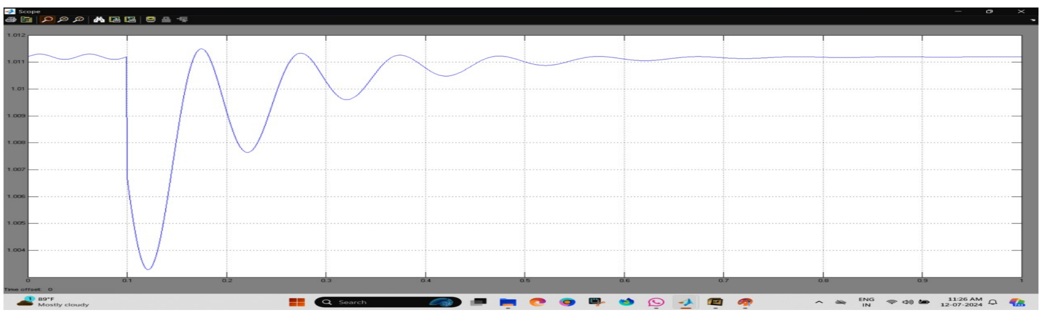

Fig.7 ASM speed FOPD (Fuzzy logic system)

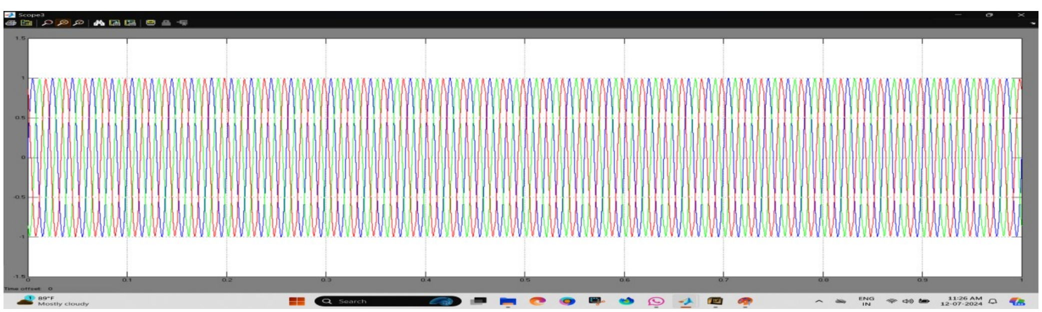

Fig.8 voltages (Fuzzy logic system)

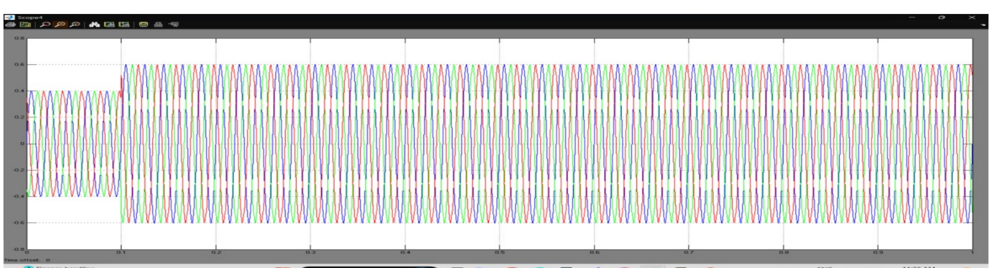

Fig.9 currents (Fuzzy logic system)

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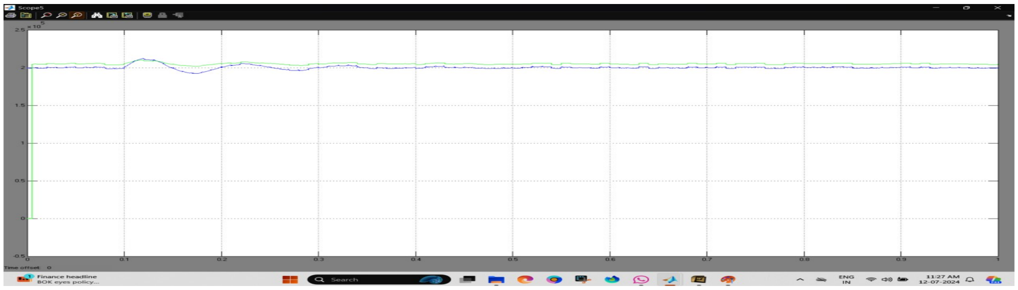

Fig.10 Active and Reactive power from ASM speed (Fuzzy logic system)

At interval t=1sec, 50kW of load is added to the system. The comparison of the frequency response of all four controllers is captured as shown in Figure. In comparison to other controllers the F-FOPD*mu* controller recovers the drop in frequency from 49.80 Hz to 50 Hz within few milliseconds, by cutting down the excess power taken by SL shown in Figure. The maximum overshoot, observed in frequency of F-FOPD*mu* controller is 50.02 Hz, much less than the frequency overshoots of the other controllers under discussion. The ASM speed plunged down to approximately 1.0094 p.u. from 1.011 p.u. and returns to 1.012 pu after the frequency returned to 50 Hz shown in Figure. As required, the voltage retains at 1 p.u. without any oscillations Figure. The added load also effects SL current which increase from 0.4 pu to 0.6 p.u. in steady state, Figure. The total load in the system is 457 kW out of which 100 kW is the fixed load whereas the remaining 357 Kw is the secondary load (SL). As soon as the added 50 kW consumer load is turned on, the power absorbed by SL slowly plunged down to regain the frequency to its supposed value. The power from WES increases up to approximately 238 kW from 200 kW and then falls to approximately 191 kW before becoming stable at 200 kW within the interval of 1 second. The synchronous condenser reactive power increases up to approximately 10 kVar when load increment goes to 220 kVar from 210 kVar and finally come back to 216 kVar once the system stabilizes shown in Figure.

Extension system:-

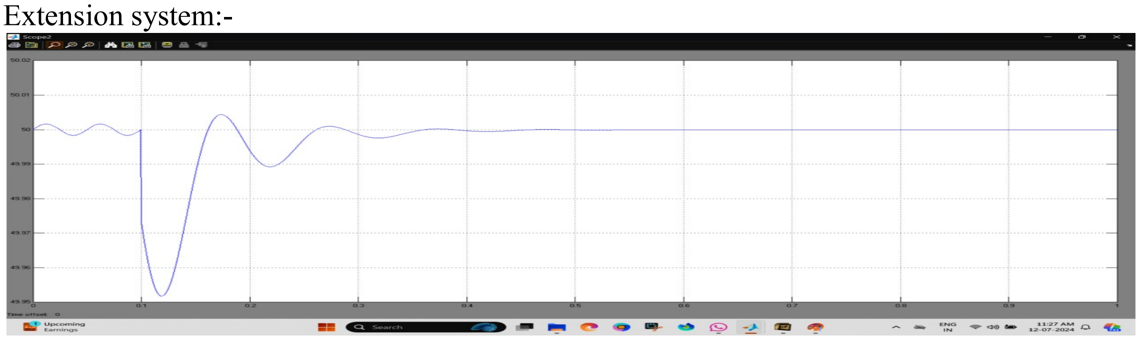

Fig.11 Frequency response FOPD load increment (ANFIS system)

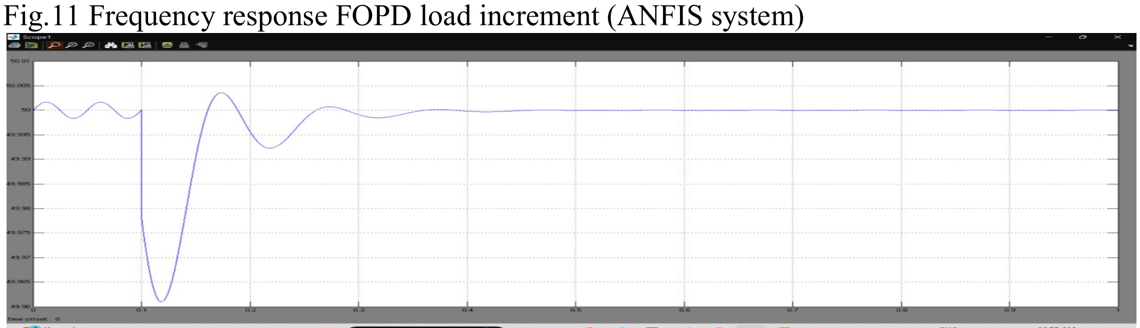

Fig.12 Frequency response F-FOPD load increment (ANFIS system)

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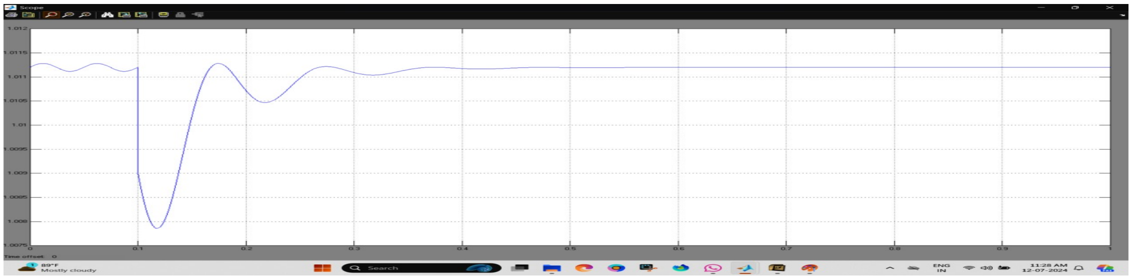
Fig.13 ASM speed FOPD (ANFIS system)

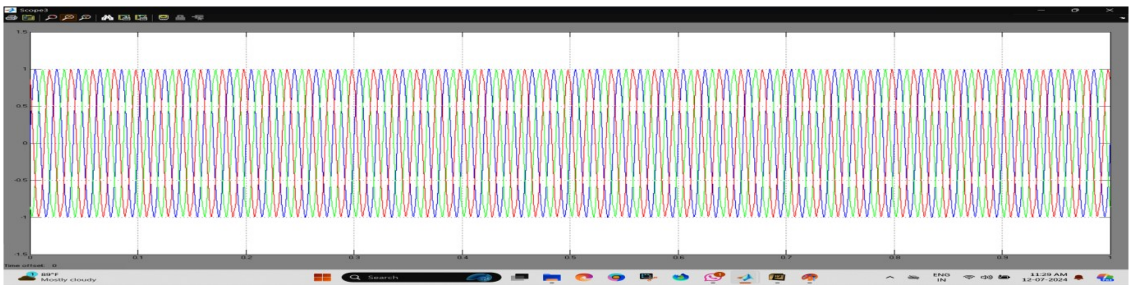
Fig.14 Voltages (ANFIS system)

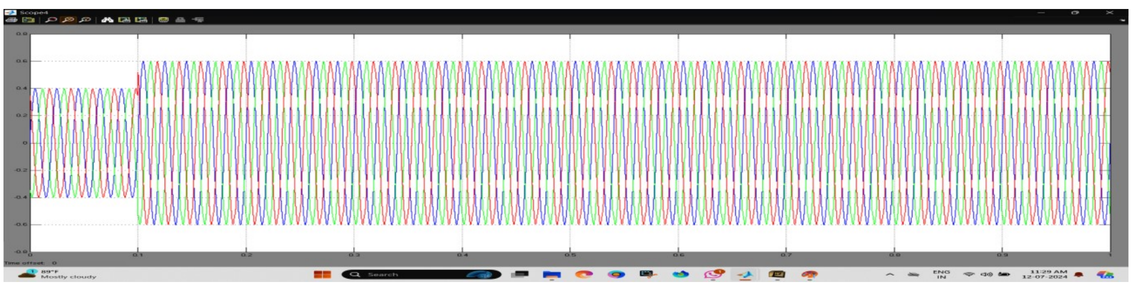
Fig.15 Currents (ANFIS system)


Fig.16 Active and Reactive power from ASM speed (ANFIS system)

Case-2:-
Proposed system:-

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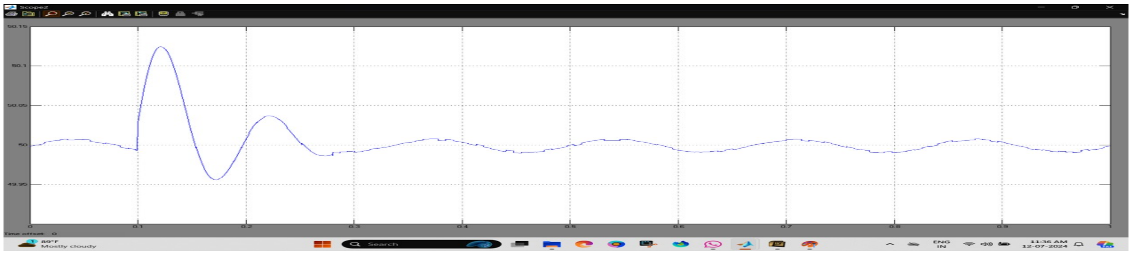

Fig.17 Frequency response FOPD (Fuzzy logic system)

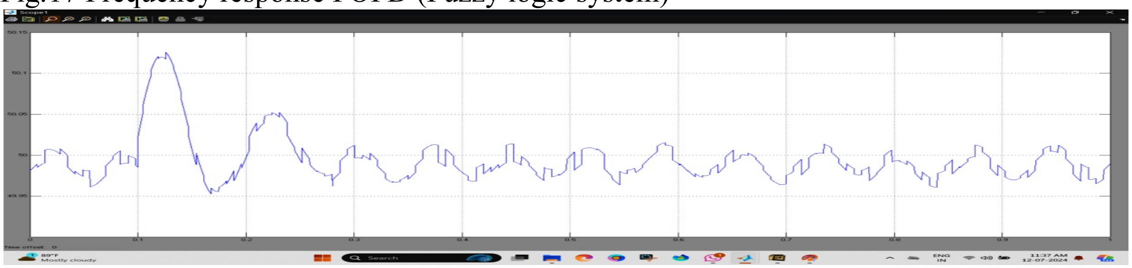

Fig.18 Frequency response F-FOPD (Fuzzy logic system)

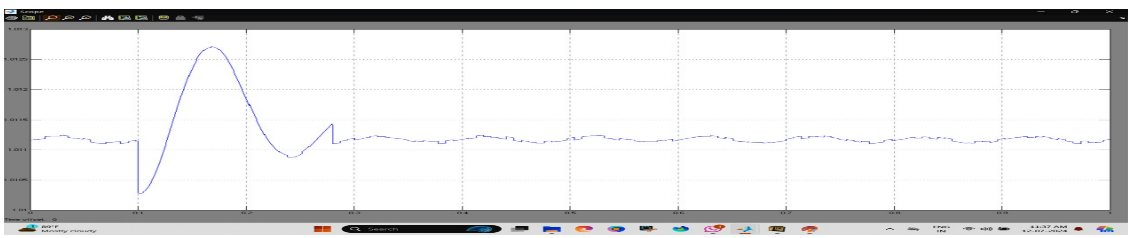

Fig.19 ASM speed (Fuzzy logic system)

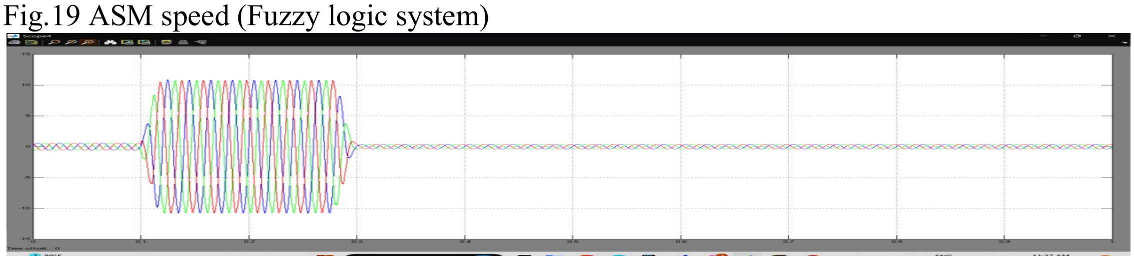

Fig.20 Currents (Fuzzy logic system)

To further the strength of the network, the performance of the system under three-phase symmetrical fault with different controllers is studied. These levels will give the idea of the fault levels and later how much the contribution of fault current may add to the existing levels of current in case of faulty conditions. Three-phase fault is applied near 50kW load followed by instant opening of a CB operated by current relay. The current relay monitors the current and it exceeds 10 kA it opens the CB. The different quantities were observed for 1 second before fault occurrence and nine cycles after clearance of fault and monitored behavior of system in figures in the following sections. The system frequency in case of 50kW load decrement at 1 sec is indicated in Figure. It can be observed that the frequency overshoot and recovery of discrete time F-FOPD*mu* is better than the other three controllers. The result displays very small jaunts of frequency that dampens down very fast and efficiently. The obtained response will clearly highlight the robustness of the four controllers and the performance of F-FOPD*mu* compared to other controllers. Similarly, the response comparison in ASM speed (in p.u.) of the four controllers is given in Figure, and the difference in ASM speed of the two most robust, FOPD*mu* and F-FOPD*mu* is shown in Figure. It is observed that voltages run

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smoothly like predisturbance values. The currents however adjust to new stable values so that the decrease in the power demand can be adjusted without voltage fluctuations, Figure. Based on the experimental analysis, the fault current of 10 kA flows through the breaker was during the threephase fault. The CBs are designed based on their ampere rating. The ampere rating is the maximum level of continuous current the breaker can withstand. Based on the simulations it was observed that around 10 kA current flows for 50 kW load whereas around 25 kA flows for 75 kW load. The relay operates as the fault current
exceeds 10 kA.

Extension system:-

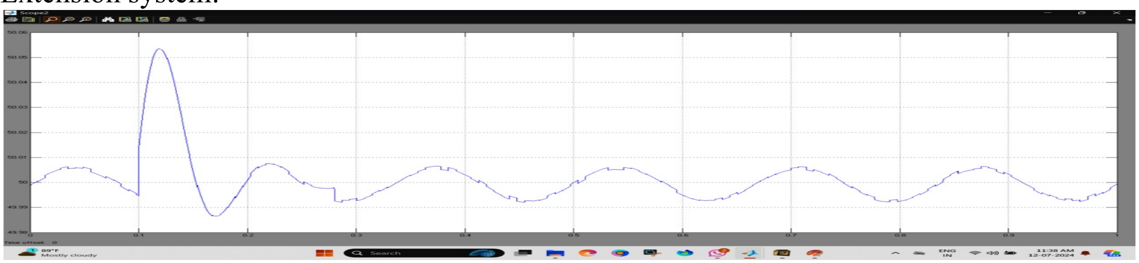

Fig.21 Frequency response FOPD (ANFIS system)

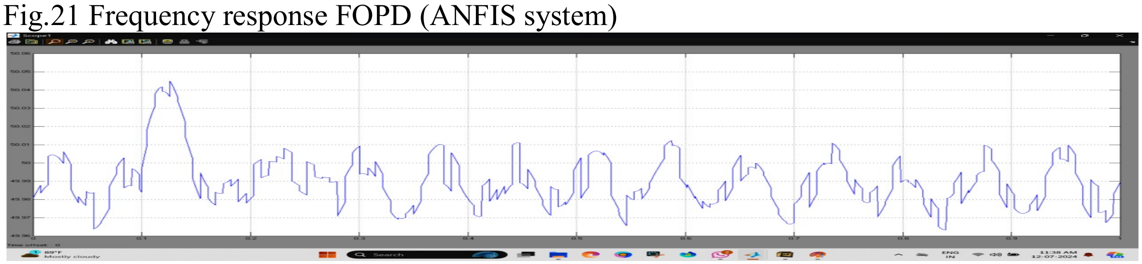

Fig.22 Frequency response F-FOPD (ANFIS system)

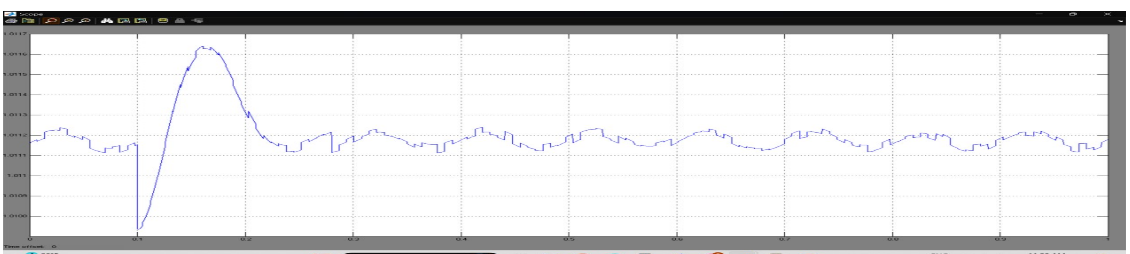

Fig.23 ASM (ANFIS System)

Fig.24 Currents (ANFIS system)

Case-3:-
Proposed system:-

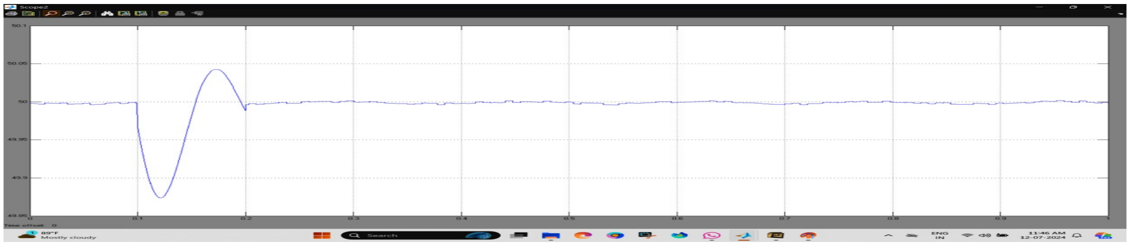
Fig.25 Frequency response FOPD (Fuzzy logic system)

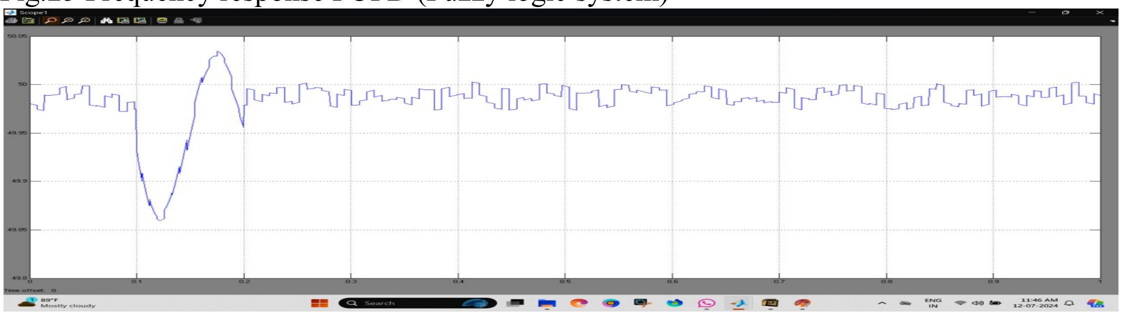
Fig.26 Frequency response F-FOPD (Fuzzy logic system)

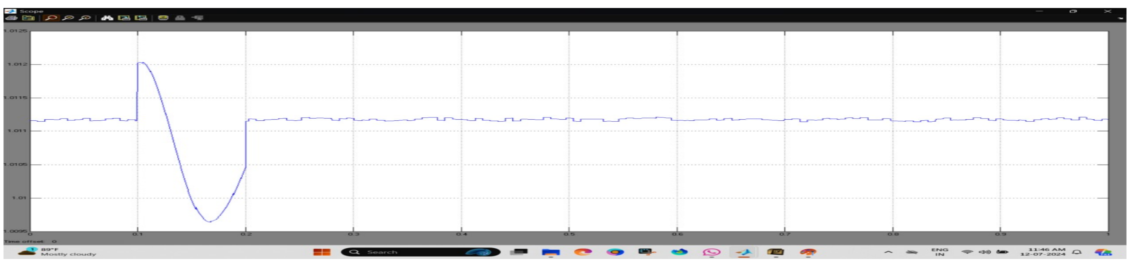
Fig.27 ASM speed (Fuzzy logic system)

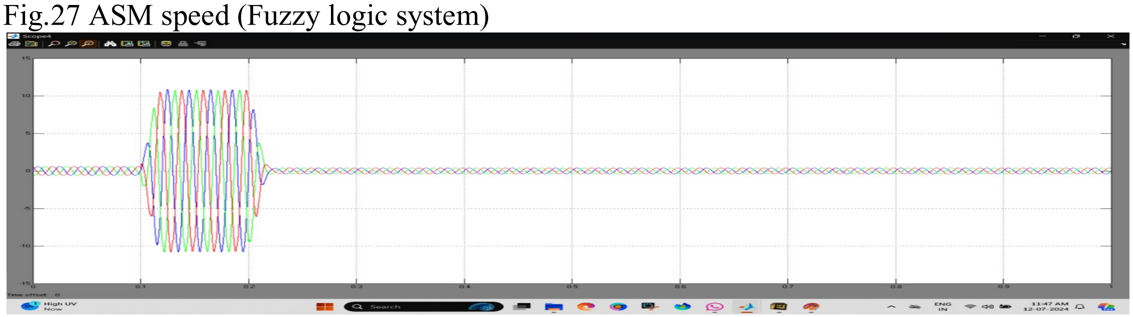
Fig.28 Currents (Fuzzy logic system)

The reason for choosing the three-phase faults is because it is the worst of all symmetrical faults, and all the protective equipment and switch gear are designed based on the short circuit current levels during these faults. The system should come back to its steady state values after 5 cycles with complete tripping of a circuit emanating towards the load. The fault is considered in the closest vicinity load i.e., right at the load bus bar of 50 kW, cleared in 5 cycles i.e., 100 msec, as normal clearing time because the breaker does not operate instantaneously but with the delay of 5 cycles. Results plotted in Figure shows very small jaunts of frequency that dampens down very fast and efficiently after the clearing of fault. The recovery of ASM speed is shown in Figure. Hence, the proposed controller is robust enough to prevent the system's frequency from collapsing even with the delay in CB opening.

Extension system:-

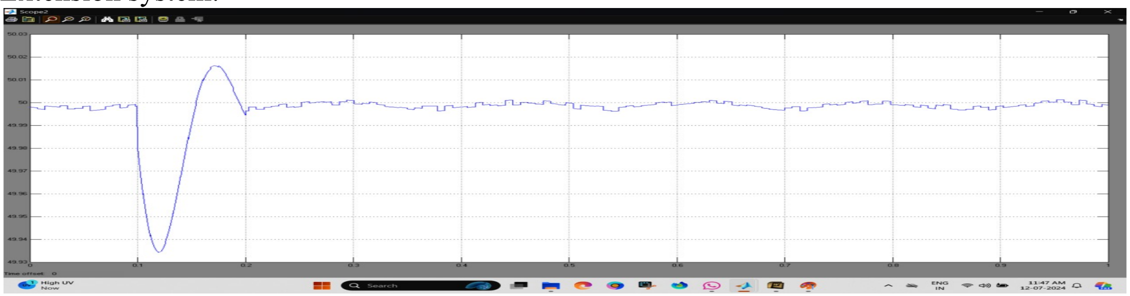

Fig.29 Frequency response FOPD (ANFIS system)

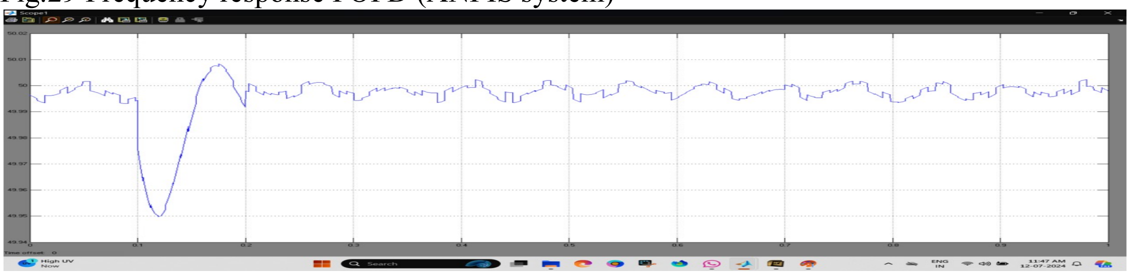

Fig.30 Frequency response F-FOPD (ANFIS system)

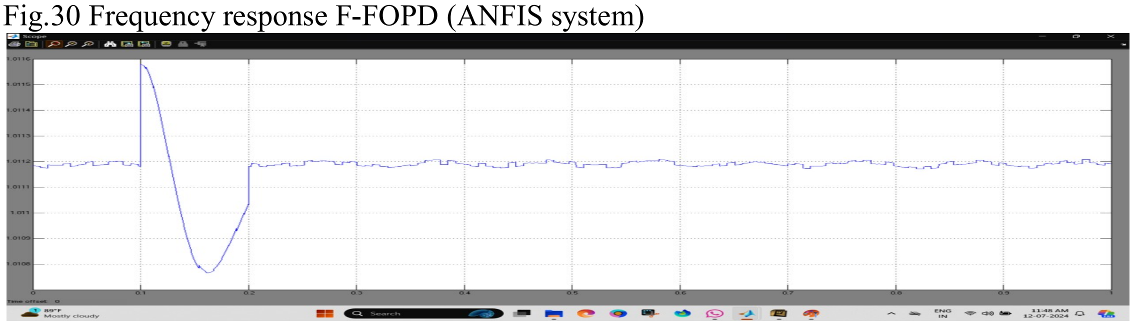

Fig.31 ASM speed (ANFIS system)

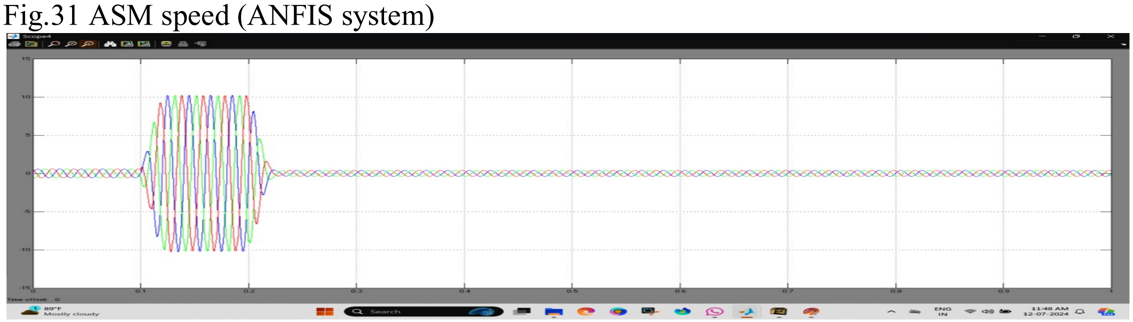

Fig.32 Currents (ANFIS system)

CONCLUSION :

A new distributed control for load frequency control of the hybrid system having wind, solar PV, fuel cell, and battery energy storage has been proposed and demonstrated. The frequency of the system is adjusted by controlling the power absorbed by secondary load. The introduction of additional tuning factor ''μ'' in the control system, increases the freedom of FOPDμ over the conventional PD controllers. This gives FOPDμ better control mechanism to enhance the performance character. It improves the response time and has less overshoot and settling time. The proposed controller is the most robust among the given family of controllers since it exhibits higher performance and is capable enough to recover the system's frequency even under the 3-phase fault injection. Moreover, the study of this hybrid scheme also suggests that inclusion of small rating diesel generators, with zero input/output, in this scheme could help recover the system better. This conclusion is based on analyzing the performance of the controller in dynamic load conditions as well three-phase symmetrical fault application, with delay of 5 cycle in circuit breaker operations. Further improvements can be composed in the modeling of the system's controller. The hybrid structure can be optimized using soft computing techniques such as PSO or GA to enhance their ability regarding LFC problems. Moreover, someone can carry out the comparison between the distributed and centralized controlling scheme for the proposed Hybrid System. In that case a central switching algorithm needs to be added to the system that regulates working of both the controllers. The performance analysis of the same hybrid system with centralized controller instead of the distributed scheme is hence a gate way to new research. Also, hybrid concept of controller can be implemented to improve the computational time. Apart from these other renewable resources like biomass, small hydro power plants can be interacted with asynchronous wind generator instead of fuel cells or PV to study with combination of the systems that will give the most economic results for LFC.

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