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A novel technique for stand-alone hydropower plant

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ABSTRACT

Stand-alone hydropower plant is a major energy source in grid isolated zone because they do not require dams to be built. In a stand-alone hydropower plant Voltage and frequency, instability is caused by the load variation. This can cause the alternator to spin very quickly or very slowly, causing the induced voltage and output frequency to rise or fall. Furthermore, if the rate of alternator growth is too high or too low, the load appliances connected to the generator can undergo huge damage. For optimal overall performance of a small hydropower plant, generated voltage and frequency must be within the required range. To overcome these issues, a system is discussed in this paper. The proposed system not only stabilizes stand-alone hydropower plant output through an electronic load control system but is also easy and price-effective. Electronic load controller managed small hydro energy generation that takes into vital parameters, i.e, stabilization of both voltage and frequency despite variable consumer load. The presented technique consists of PID and fuzzy logic control system and also a couple of DC motors interconnected with an H-bridge to control the water valve known as a gate. The proposed control system also consists of several dummy loads to dump the extra generated power to keep the output power constant and to overcome frequency variations. For increased efficiency and life span of the generator, dummy loads used are switched only at zero crossings of a sinusoidal signal. The proposed system is implemented on both Simulink/MATLAB and Proteus. The simulation results prove that the presented technique overcomes the challenges of stand-alone hydropower plants.

1. Introduction

The requirements of energy sources have increased a lot in the past few years because the world population has increased triple-fold. In the present time, the universal supply of energy is catered by using fossil fuels. Fossil fuel energy resources are collectively known as traditional forms of energy and there is another issue with these fuels that they are diminishing at a rapid rate as well as they do not a cost-efficient source of energy [1]. Moreover, these fossil fuels usage has an adverse impact on human society and its environment. Since the expense of transmitting wires is very high, therefore electric current is not sent to the far-off hill stations[2]. Therefore a huge difference exists between the delivery and needs of the electric current [3]. Furthermore, the trade-in fossil resources have an extremely huge expense.

Adverse contamination in the air is also produced by these fossil fuels. For diminishing the side effects of such traditional fossil energy sources, there is a need for the invention of an effective as well as cost-efficient power generation methodology. Nowadays, the demands for reusable energy sources have increased a lot over the traditional sources of energy

[4]. There is a great need of transforming the energy sources from traditional fossil fuels towards reusable power sources to surmount all the global issues of fossil fuels usage. Although reusable energy sources are not that effective as traditional energy resources, they provide other benefits like they are less expensive, more nature welcoming, and more dependable. By using various methods, humans are in search of finding the methods for enhancing the efficiency rates of these reusable power sources. Research experts have worked a lot for enhancing the reusable energy supplies so that these energy sources are available to hilly stations as well as they also become cost-effective sources of energy[5]. Due to all these experiments, reusable energy sources are becoming more reliable and more efficient in all manners. There is great reduction in the risks of worldwide warming, most terrible atmospheric contamination, reduction of traditional energy resources as well as universal weather modification. The eventual basis of power is the solar system, however, the most strong energy resource is thought to be hydraulic power in comparison with solar and turbine sources[6]. The overall procedure is that the potential power of water due to its height is transformed into the kinetic power in a hydraulic power system, and then the motor associated with the turbine system starts rotator motion and hence power is produced. By using a generator linked with a turbine, the electricity is produced from the potential power of water.

Since the transfer of power towards the hilly areas is a very expensive phenomenon, therefore electrical power is not distributed in those areas. The electricity is transferred to hill stations and villages by using mini hydraulic energy systems at very little expense. Within the pastoral locations, the number of individuals is fewer, as well as the broadcast system expenses, are extremely lofty. Due to the presence of creeks, the potential power of water can be made available in the rural areas which can then be used for producing energy for the villagers. In the hilly stations, the use of water energy, wind energy as well as solar energy is quite suitable due to the lesser number of people living there [7]. Therefore, the provision of electricity can be made possible in rural areas by the use of these natural energy sources. It means that if an appropriate controller circuit is used, then the electric energy from the heads can easily be given to the individuals of the nearby hilly areas. In this case, both micro, as well as mini hydraulic energy set-ups, are the perfect choices to be used in the hill stations. The expenses of transferring energy can be minimized by using these available power sources for providing power to other grid stations. Mini hydraulic energy stations act as the most well-organized, elastic, vigorous, less expensive as well as the confirmed reusable energy production technique.

Pakistan is still in the developing stage, so it is the victim of a lack of enough electricity. The differences between the requirement and the deliverance have steadily grown that acts as the basis for resulting in the raise of a requirement for and order of power sources. In Pakistan, the adverse condition of electric power is that there is no supply of energy in village areas, moreover, the supply of energy in cities results in insufficient use and load shedding [8]. There is a huge gap in the need and the production of energy and it is steadily growing, ultimately resulting in a lack of proper energy supply. The amount of energy supply in urbanized areas of Pakistan is decreasing whereas there is no supply of energy at all in the rural areas. Nowadays, the extreme adverse condition of electricity depreciation is happening in Pakistan. Due to expensive traditional fuels and load shedding, many industrial sectors have shut down their businesses. The conditions of rural areas are worst because there are no grid stations for electricity supply whereas the supply of power in urban areas is equivalent to none, leading to load shedding and power breakdowns. There is a great need of using all the available heads by using natural fuels for handling this crisis. The MHPP systems play an important role in the utilization of reusable power sources as they help to transmit energy to hilly areas where lesser individuals stay and where the expenses of power transition are out of reach. Now only mini, as well as micro hydraulic energy systems, are the expected systems that can bring progress in the rural areas of Pakistan. Almost three hundred and fifty-six MHPs have been initiated by the government of KPK and its main purpose is to provide the facility of electricity to the northern parts of KPK who have no access to the grid station.

For the set-up of MHPPs, those places are preferred in which the supply of water is uninterrupted so that there are no changes in the put-in power to the turbines via the flow of water[9]. Moreover, the disturbance is created within the occurrences and the voltages due to differences in the energy demands of on-grid and off-grid stations [10]. The variations in frequency happen when there are changes in the loads which happens due to changes in the flow of water leading to variations in the rotator pace of the turbines. For maintaining the frequency as well as the voltage of the generators to a fixed number, there should be a balance between the produced energy and the consumed energy. If the produced energy is greater than the consumed energy, then the occurrence would be exceptionally high and vice versa. MHG has been employed for managing the flow of liquids in traditional hydraulic plants. Hydro-based managing refers to the procedure for dogmatic and supervising the pace of water towards the wind systems along with the composing need for maintaining the pace as well as the revolution stability. A hierarchy-based speech-filled PLC is used that is taken as the mind of the entire mechanism. By taking results from the PLC, a mechanized set-up is established that works under the greasy power. MHG's refer to the complex measures that need precision in the blueprints. To correctly use the flight valves and inlet systems, a bulky ball-like system is used by MHGs. In MHPPs, the discussed set-up results in greater than 30% of the entire expenditure. The use of MHG in the MHPP system is not cost-effective as it requires higher installation costs as well as needs greater repairing prices. MHPs are not installed within the governing systems[11].

In the MHPP system, the best substitute for MHG is ELC i.e. Electronic Load Controller because it has a unique basic design as well as it has a greater controlling capability. ELC is an electrical circuit that tends to maintain the continuous load above the motor irrespective of the changes in the user's loads. The mechanical energy is transformed into electronic energy by the motor, and in the case when the produced energy is greater than the user’s needs, then the pace of the turbine will automatically be enhanced that will lead to the increased frequency value [11]. This variation in the set frequency is catered by the electrical control system because it turns on the ballast loads so that additional energy is sent to the dummy loads. Afterward, when the users’ loads are turned on, this will lead to the reduction in the occurrence, hence the ballast loads will be turned off by the associated ELC. Fig. 1 shows that whenever the variations in the user's loads are detected, then the setup makes necessary changes whereby the entire load system attached with the motor stays steady.

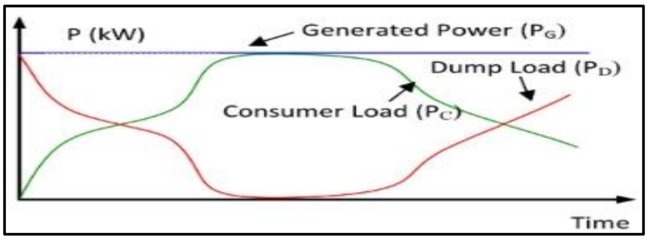

Fig. 1. Basic working of electronic load controller

For reducing the variations in the frequency and pace of the motor, materials like wind and liquids are used for making ballast loads so that additional energy is properly rerouted[12]. By getting a sign from the controlled chip system, the linked triacs, thyristors, and IGBTs i.e Insulated Gate Bipolar Transistor start the work of sending additional energy to the ballast loads [13]. So there is no requirement of the worker since the frequency of the generator will be kept at 50 Hz naturally. The ballast loads are turned off when the load is high whereas when the user's load is lesser, then the ballast loads are kept on just like depicted in Fig. 2 [14].

The basic theory of ELC is to guarantee that energy produced from the motor appears to be similar to the energy being used by the load [15].

Generated Power = Power of the consumers’ load + Ballast load power

$$P_g = P_{cl} + P_{dl} \tag{1}$$

The better actions of ELC are mainly visible in a separate MHPP system. However, a great amount of power is wasted in this system as well as ripples are generated while the switching process. Moreover, if the produced energy is more than 100 kW, then greater resistor loads are needed[16]. The suggested mechanism is the linking of the DC motor with the set-up of ELC so that the energy of the liquid is easily tuned with the user’s loads, hence decreasing the power dissipation. Arduino Mega control system is used for switching off and on of the ballast loads if there are any problems, however, after some time, the message will be transferred directly to the DC system [17].

There are two main kinds of issues with the MHPPs. The first problem is either the enhancement or reduction of the water pace. If there is an increase above three cusecs or there is a reduction below 0 cusecs, then some type of electrical setup is needed for controlling the system. In the second type of problem, there are problematic turning off and on of the users loads[18]. Therefore, for managing the yields of MHPP, simply ELC is employed and further the messages are sent to the electrical control system [19].

There are total nine sections of this paper. The second part discusses the problem statement, the third part discusses the contributions for the proposed system, the fourth part provides methodology used for designing of the proposed system, the fifth part discusses the mathematical modelling proposed system, the sixth part discusses the simulink model control system, seventh part shows the results and discussion, eighth part discusses the Proteus model and the final section of this research paper includes the conclusion.

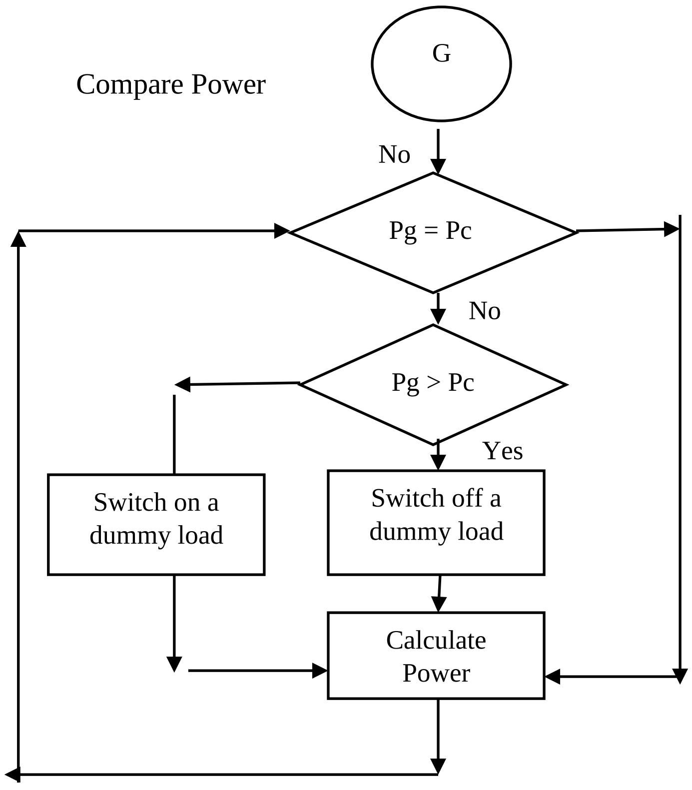

Fig. 2. Flowchart of ELC

2. Problem Statement

The reason for frequency unsteadiness as well as problems in the set-ups includes load changes at the micro-hydropower plant system. Eventually, the pace of the motor will be varied either to move at greater speeds or reduced speeds which will cause the motor frequency to increase or decrease. Moreover, the equipment of the users can be burnt out if the speed of the motor goes too high or too low. The frequency of the motor must be according to the set values so that the efficiency of the hydropower plant can be enhanced. The use of mechanically governed systems just linked in the traditional systems becomes highly costly in a micro-hydropower plant. The use of an electronic load controller eliminates all these issues and is more cost-effective. However, it leads to harmonics if the power is greater than 200kW. Moreover, the use of bulky loads destroys the generator and can tear the turbine shaft system.

3. Contribution

Research contribution will be:

1. Maintaining the yielded energy of the motor in accordance with the user's loads.

2. Regulating the steady frequency as well as the voltage of MHPPs and also developing requirement energy.

3. Experiment with the replicated set-up of the projected mechanism in the labs.

4. Devising a basic and profitable electrical-mechanical controller set-up intended for MHPP'S.

4. Research Methodology

Different control strategies and their pros and cons are discussed in section 1. It can be concluded from that discussion that the mechanical governor system is less feasible owing to its heavyweight, high rate, and expert requirement for its operation. Another method which is an electronic control circuit that first converts AC to DC and further converts that DC to AC also known as back-to-back is also inconvenient because it is not only expensive but also produces distortion i.e., harmonics. Yet another method discussed was Electronic Load Controller (ELC) which maintains the voltage and frequency of generator essentially constant; nevertheless, it only operates at full load. Because of heavy load, damage of shaft and built is also expected. Moreover, ELC requires a constant water flow for its operation, and it fails to deliver if water flow decreases the threshold value. Additionally, water flow needs to be controlled manually as the system has no built-in control on the flow of water. Every single of these systems has some shortcomings and are not completely fit to fulfill the required purpose. The method implemented in this paper is the combination of these three that combines the advantages of these three and suppresses most of their shortcomings. The method discussed is a robust electromechanical control system that produces the best results for output control of micro hydropower plants (MHPP).

5. Mathematical Modelling

The generator selected for the modelling is a synchronous generator. The circuit also consists of ELC (electronic load controller) and a stepper motor. The flow of water varies all around the year. Kinetic energy of moving water converts into mechanical energy by the relation.

$$P_w = \frac{1}{2}\rho A V^3 \quad (2)$$

where, ρ is the density of water, given as 1000kgm^{-3}, v is the speed of water in ms^{-1} and A is the swept area of water turbine in m^2. Power coefficient of performance (C_p) is given as

$$C_p = \frac{Tt*w}{0.5*A*V^3} \quad (3)$$

The torque of the water turbine (T_s) is given as

$$Ts = \frac{P}{W_s} \quad (4)$$

Where $\boldsymbol{\rho}$ is the water turbine power and $\mathbf{W_s}$ is the speed of the rotor of the turbine.

The generated power is supplied to the consumer load. Dummy loads will be turned on if in case the generated power is more than that required by the load. Hence generated power P_{og} is the sum of consumer load power P_{dl} and dummy load power P_{cl}

$$P_{og} = P_{dl} + P_{cl} \tag{5}$$

The standard equation for the speed of the synchronous generator N_s which is directly related to the frequency of voltage generated f and inversely related to the number of poles of generator p is given as

$$N_s = 120\frac{f}{p} \tag{6}$$

S domain representation of input Gg(s), excitor Ge(s) and proportional-integral controller Gc(s) is as follow

$$G_g(s) = K_G/t_g(s) + 1 \tag{7}$$

$$G_e(s) = 1/t_e(s) + 1 \tag{8}$$

$$G_o(s) = K_p + K_I/s + sK_D \tag{9}$$

Hence, the closed-loop transfer function GC(s) as given by becomes.

$$G_{C(s)} = G_{g(s)} . G_{e(s)} . {G_{o(s)}}/{1\, G_{g(s)} . G_{e(s)}}$$

PSO (particle swarm optimization) algorithm is used to find the values of gains of PID controller K_P, K_I, and K_D.[20] PSO tunes these gains under different conditions and circumstances and is based on swarm intelligence and movement. PSO was developed by Kennedy J. in 1995.

It has been proved effective for multiple problems of search and optimization. Solution space occupies some particles, and these particles after specified iterations occupy a local and global best solution [21]. The resulting optimum value replaces the one from the previous iteration and is shared with other particles. Fig. 3 shows the framework of the PSO algorithm.

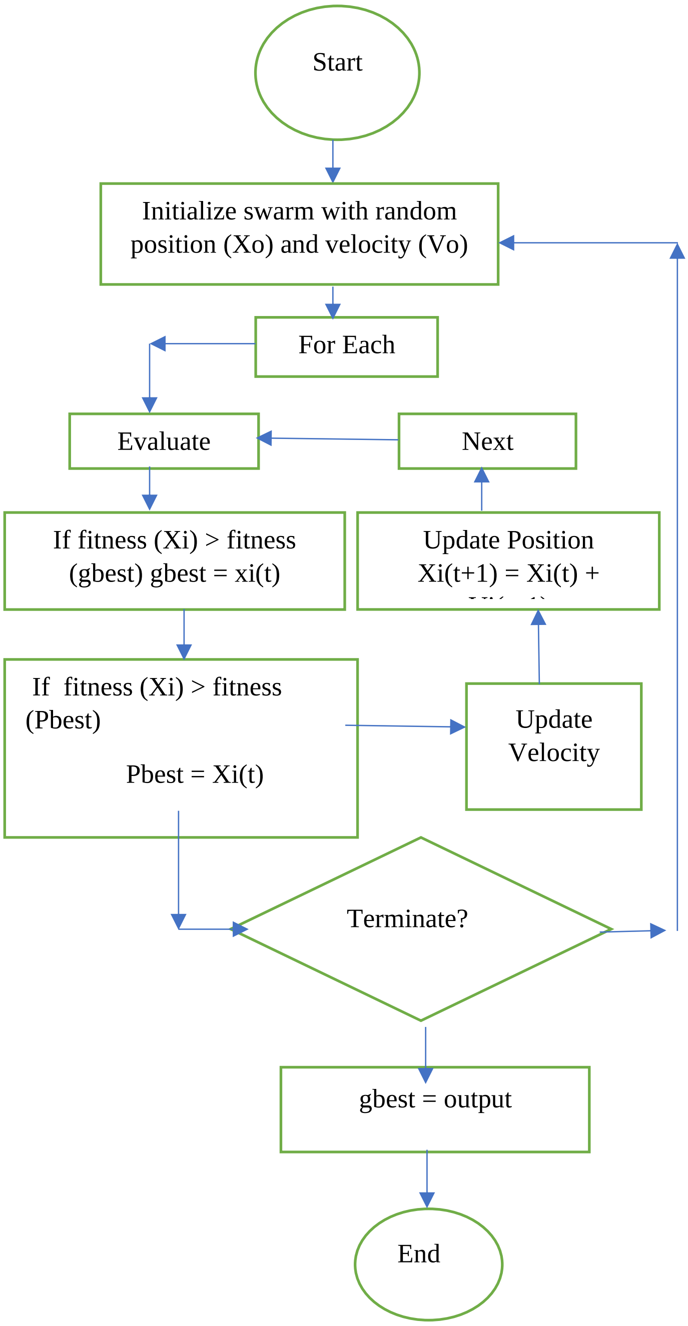

Fig. 3. Particle swarm optimization [22]

First of all, particles are initialized with numerous values to cover the whole space available. Then the controller is started and once settling time is reached, it computes the position and fitness value of particles. [23]. Consecutive particle values are compared and the better of the two is chosen to be the local best, then this selected best is compared with the next value and they both compete to gain the title of local best. At the end of the whole iteration, the chosen local best is called the optimum value. [24, 25].

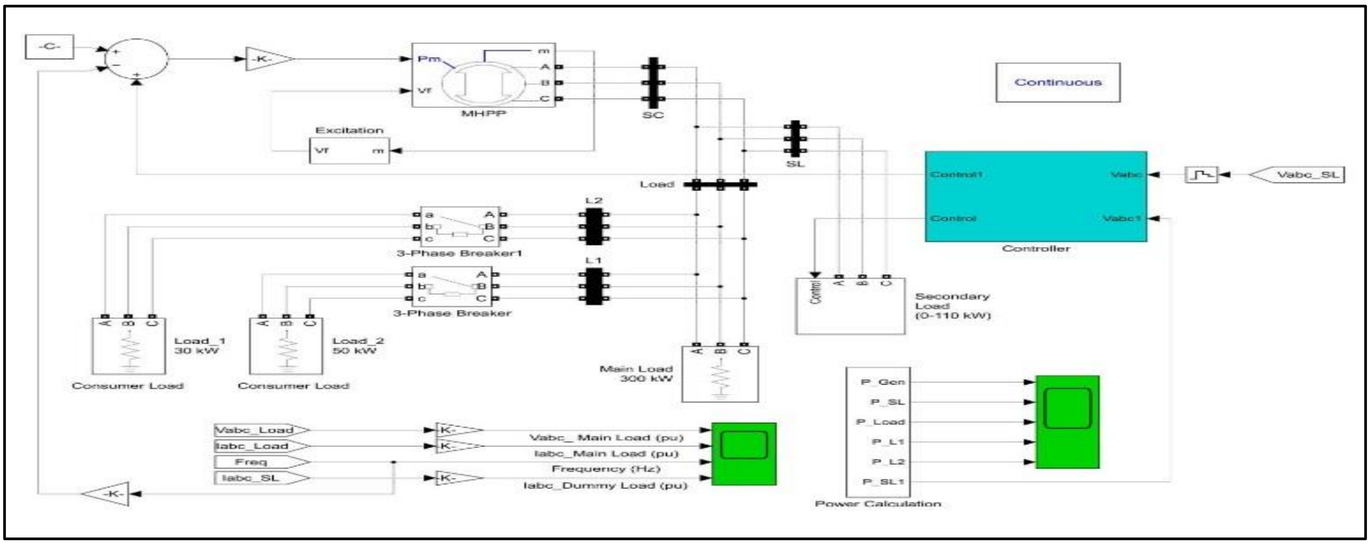

Fig. 4. Simulink model of proposed electronic load controller

6. Simulink Model Control System

The schematic circuit of Fig. 4 is implemented on Simulink (MATLAB). A synchronous generator is used to represent a 100kW isolated MHPP, and its excitation block is a pure DC source. PID controller is used to control the power of this isolated MHPP by giving a signal to dummy loads, which are binary weighted. Additionally, the zero-crossing technique is used, that is, switches to the dummy load turn on or off at zero crossings of the sine wave. The firing angle is calculated only at zero crossing and then PWM is used to keep any load on or off depending on the error signal to the PID controller.

6.1 Electronic load controller

The box labeled 'proposed ELC' is the Electronic Load Controller (ELC) block. The only input of the ELC block is the frequency of the generator. The reference frequency is subtracted from the generated frequency. The reference frequency is given by a constant block, which in this case is 50Hz. Their difference is the error in frequency which is then given to PID controller block. Pulses are generated by PID in response to different error values. The output of PID controller is fed to the pulse decoder and from there to the sampling system block. The output of the sampling system block is the output of the whole ELC block which then goes to a dummy load. Fig. 5 shows the ELC block.

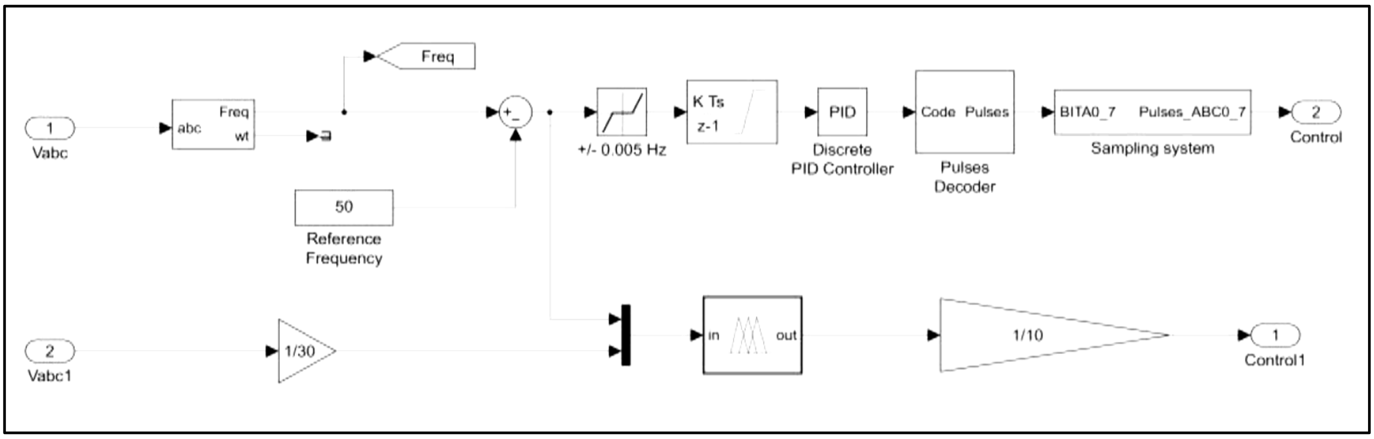

Fig. 5. Electronic load controller (ELC) block

6.2 Logic control system

PID controller is used to maintaining frequency in accordance with a reference frequency, while a fuzzy logic control system is used to control the DC motor. DC motor is required to control the valve of the water that is given to the power plant. When a frequency is high it implies that that water flow is increased and vice versa. So, one input of fuzzy controller is frequency. A second crucial factor is consumer load, which is not constant. Hence, the requirement of the power for consumer load also varies largely. Power plants should generate the power in accordance with the requirement i.e. when there is more requirement more power should be generated. So, the second input of the fuzzy controller is required power by the consumer load. The fuzzy logic controller takes these two inputs and provides robust results using the partial factorial method. Fig. 6 shows the fuzzy logic controller designed in Matlab.

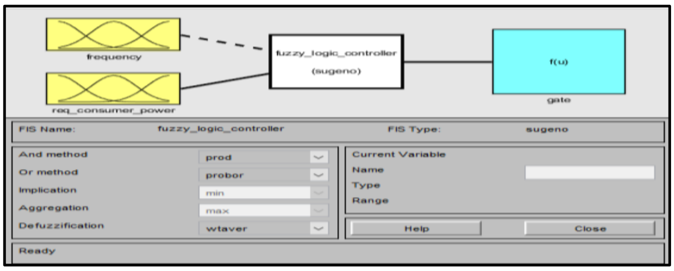

Fig. 6. Fuzzy logic controller

7. Result and discussion

The mini-hydro power plant is directly connected to the load, with no control signal, hence no dummy load turns on. Fig. 7 shows the generated voltage, frequency, and current consumed by load and dummy load.

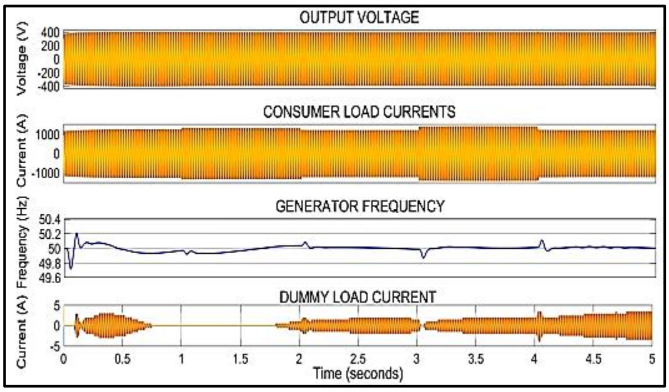

Fig. 7. Voltage, current, and frequency graph without controller

Fig. 8 represents three different powers, one is the power generated by a power plant, the second is the power consumed by main load and the third is the power consumed by the dummy load.

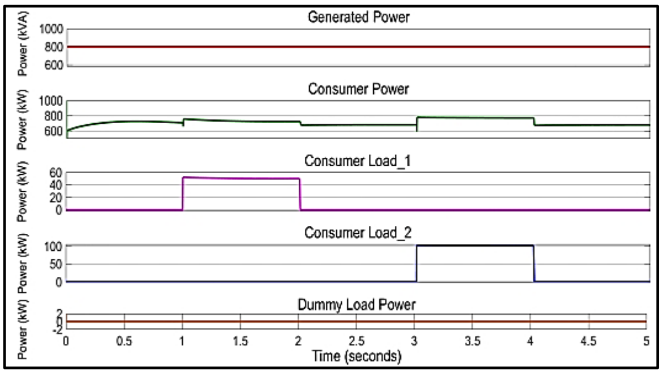

Fig. 8. Power graphs without controller

The frequency of the generator is increasing from the required 50Hz to 55Hz and it is even increasing more. Even this 5Hz increase in frequency can cause serious damage to the appliance connected. To resolve this issue, the controller is connected to the power plant. The output voltage, current, and frequency plots with a controller are shown in Fig. 9.

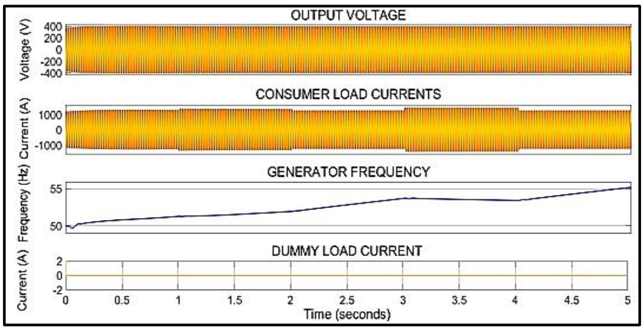

Fig. 9. Voltage, current, and frequency graph with controller

It can be observed from Fig. 10, that when a power plant is connected to a controller, generator frequency does not increase without bound, but it sticks around 50 Hz with ±0.2 Hz difference at all times.

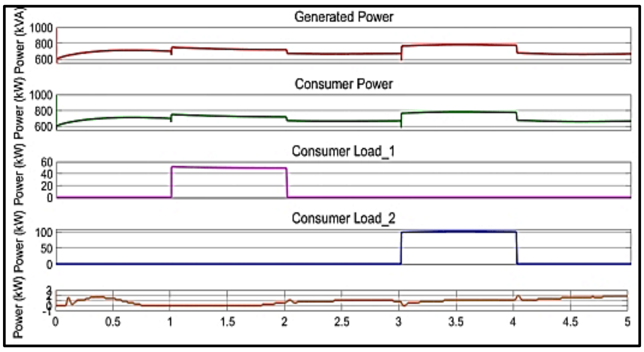

Fig. 10. Power graphs with controller

7.1 Electronic Load Controller

The electronic Load Controller (ELC) is connected for the study purpose and to compare its performance. Unlike PID, ELC controls higher frequency which is a huge benefit because it prevents unnecessary damage in case of high frequencies. But it also has a number of shortcomings. One major shortcoming is that it can't control water that will fall of a turbine, hence resulting in non-constant power generated. The second mentionable shortcoming is dealing with high current, which results in excessive power loss during switching.

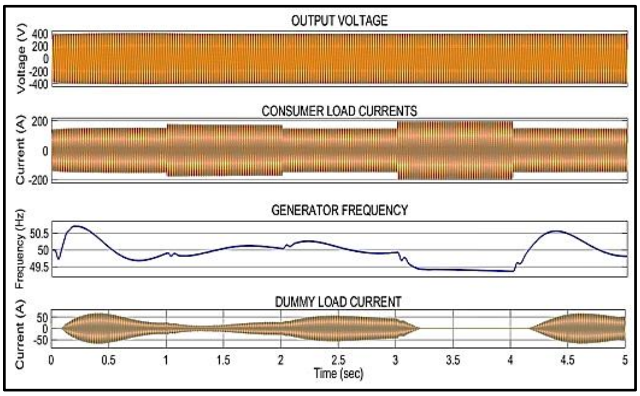

Fig. 11. Electronic load controller working

8. Proteus model results

The results are taken at different values of frequencies and their effects on the dummy load switching. One state where output and frequency of electricity produced remain effectively desirable and no gate is opened, and no dummy load is active and DC motors are in an off state. When the gate is closed to keep frequency and voltage on track without having to switch on any dummy load. Where frequency is higher than reference frequency and different dummy loads are switched to keep it in accordance with reference. 1-3 dummy loads could be seen working in these graphs via LEDs with different gate voltages and DC motors could be seen in action. In the trip voltage case, where all six dummy loads are on, the DC motor is operating at full speed and the trip voltage indicator (LED) is turned on. Frequency has fallen below the reference frequency level. Hence to meet this shortcoming, the gate is opened at different percentages paired with dummy loads.

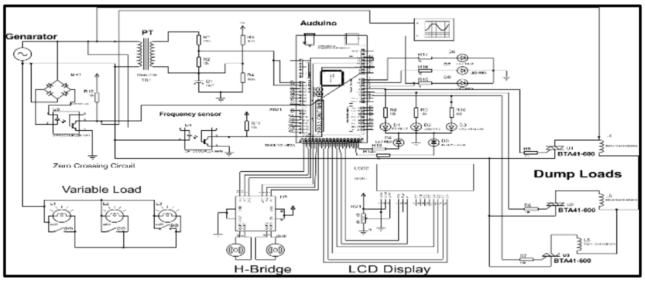

Fig. 12. Proteus model

8.1 Comparison between the controller technique

Various control techniques have been implemented in this paper Different techniques have played different roles in the stabilization of frequency. In this section, the output frequency of the generator in response to different control techniques is plotted on one graph to study how these control techniques compare with each other.

Fig. 13 depicts the output frequency of the generator in response to various control techniques.

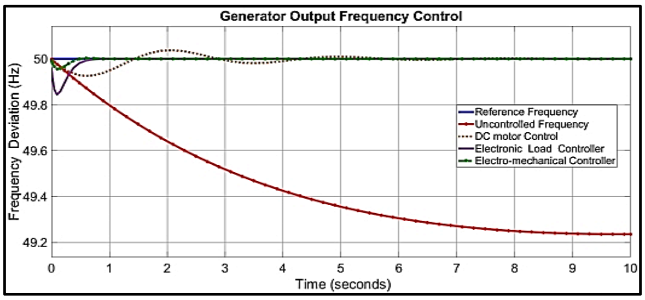

Fig. 13. Comparison between control techniques

In Fig. 13, the blue line represents the reference frequency which is a straight line on 50Hz level. Redline depicts uncontrolled frequency, that is frequency of generated output in the absence of any controller. It diverges largely from the reference value. At times, DC motor increases the water flow from the valve and decreases at other times, owing to this fluctuation and in the absence of a controller, frequency is bound to decrease.

DC motor control represented with a dotted line effectively tracks output, but its settling time is higher than any other technique. Response of electronic load controller (ELC) represented with solid magenta line is although good but its effectiveness is associated with low power application only. Not only its efficiency decreases when power is increased beyond 30kW but also it produces harmonics and transients during switching of the dummy load.

The last one is the proposed controller of this paper represented by the green line is the electro-mechanical controller. It is evident from Fig. 12, that it is tracking the reference frequency most effectively and that is settling time is least compared to other techniques. Not only that but it also reduces switching transients and harmonics.

It is suitable for both low power and high-power applications as demonstrated in mini and micro hydropower plants.

It effectively stabilizes the frequency in any power rating application with ±0.2% variation reducing harmonics at the same time. Rise time, settling time, and overshoot of these controller techniques are shown in table 1.

Table 1

Controlling techniques comparison

Controlling Technique	Rise Time	Setting Time	Overshoot
Uncontrolled	43.8sec	94.4sec	0%
PID	0.286sec	0.893sec	0.0%
DC motor	0.0155sec	8.27sec	0.0753%
Electromechanical	0.0824sec	0.629sec	0.00187%

9. Conclusion

Non-conventional or small-scale hydro plants possess a number of advantages and feasible applications compared to large-scale or conventional hydropower plants including no need for massive civil structures and huge water reservoir dams. But these small-scale water plants also have a number of challenges. The two major challenges include variable water flow around the year especially in Pakistan's northern areas and variation of consumer load attached to these generators. When glaciers melt in summer, water flow in the reservoirs increases or natural water heads increase. Moreover, consumption of electricity also changes with change in seasons or from day to night usage in general. These two challenging issues are addressed in this paper, and a control system is proposed to overcome both of these challenges. The proposed control system is an electro-mechanical system that is robust. The proposed system is tested on both Simulink (MATLAB) and proteus. Both of these models are observed under different load and generator variations. The designed system worked perfectly under all conditions in both software. The result of these and especially the result of the proteus model indicate that this circuit could easily be made on hardware and it will be equally effective. Results are presented for two types of small-scale hydro plants i.e., mini and micro hydropower plants.

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