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Automatic Frequency Control of an Isolated Small Hydro Power Plant

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Abstract - *The paper presents a new technique of automatic frequency control of an isolated small hydro power plant. Presently surplus generation due to decrease in load is dissipated in a dump load. But surplus water can be used for irrigation which is the primary requirement of the local community for their survival at large number of locations. It is being wasted in the dump load and the new scheme proposed in this paper eliminates the dump load, while the input power of the hydro plant is controlled by an on/off and a servo controlled valves. The on/off control linearly raises or lowers the generation by 30%, while the servo motor controls the generation to the required extent. It is shown that the rate of opening or closing of the on/off control valve has considerable effect on the transient response of the system. Finally, the dynamic responses due to step disturbance for different nominal loadings of the system, gain settings, rate of closing/opening of the on/off control valve are also presented.*

Key words - **Automatic frequency control, Small-hydro, Dump load, On/Off control, Servo motor, Load frequency control.**

1. INTRODUCTION

In today's world electrical energy is very essential and its availability plays a significant role in the upliftment of remote, backward or grid supply starved society. The gap between demand and supply is increasing day by day and often it is not possible to meet the demand of big consumers. Therefore, a large number of villages either have no electrical connection or getting erratic electric supply only for few hours in a day from the grid. The dependence on fuel (diesel systems) and also on grid supply can be reduced by having stand-alone generations to meet the local requirements in these areas/locations. Some of these geographical areas have large number of small hydro streams which can be used for stand alone power generation.

The energy in flowing water of small streams can be tapped by small hydro power plants. This clean source of power, therefore, plays a vital role in rural electrification in the case of developing countries [1-3]. Moreover, small hydro power has a huge, as yet untapped potential in most areas of the world and can make a significant contribution to future energy needs [4]. Small-hydro power generation is already an effective and efficient proven technology, but there is considerable scope for research and development of controls for this technology. Most of the small-hydro plants usually require a weir, and they don't require a dam or large water reservoir. Different technologies of small hydro power, innovations being developed and barriers for further development were discussed in detail in [5].

The maintenance of system parameters like frequency, voltage etc., within certain limits is essential for proper operation and efficient use of power produced. The system frequency can be maintained constant by eliminating the mismatch between generation and load. A conventional speed governor with supplementary integral control can be used to maintain the frequency constant both for grid connected and isolated mode operation. In general the generation control mechanism is not used due to prohibitively high cost; therefore, frequency is maintained by load management. A complete mathematical model for an improved load controller when applied for a micro/mini hydro, wind, diesel electric system are discussed in detail [6-12].

In a stand alone small-hydro generation system due to non-availability of storage facility, the total input has to be converted into electrical energy. Any variation in power demand is controlled by a resistive load called Dump load. Since the input to the generator is essentially constant the excess power due to decrement in load is dumped into the dump load. A combined IGBT based chopper load and switched capacitor based VAR compensator is used as load controller for resistive and reactive loads respectively [7, 13]. A complete mathematical model for an improved load controller when applied for a micro/mini hydro electric system is given in [13-15]. The concept of using electric water heater as dump load to meet the load balance is proposed in [16.]. This kind of system is proved to be cost effective when there is a hot water requirement. Mostly, the dump load is a resistive load supplied by a 6-pulse rectifier and the power consumed depends upon the system frequency with a PI controller for elimination of frequency error [10, 12], [17-19]. It is widely used in an area where there is huge uncertainty of input power and/or large variations in load [20]. Special case of dump load is reported, which consist of eight three phase resistors [11] (binary progression values) connected in series to control the power and the dump load nominal power is chosen to be 30% higher than nominal load power [21]. One of the main reasons for non-exploiting isolated small hydro power systems in the higher capacity range is due to the limitation on the size of the available dump loads [18, 19]. It is also one of the

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reasons on the existing systems that the resources are not used to the fullest available capacity.

In most of the small hydro plants it has been observed that the primary requirement of the local community is water for irrigation as their survival are depend upon it. But if electricity is available it will enhance the living standards by helping in better education, healthy, communication facilities etc. Once water enters the stream from tailrace, it requires power for pumping to the fields. Therefore, if surplus water is available before the entry to the penstock it can easily be diverted to the fields. In general the load factor of small hydro plants is less than 50%. Therefore, more than 50% water can be available as surplus if proper generation control strategies are employed instead of using dump load. A new control scheme is proposed in this paper by which the dump load is eliminated and frequency is maintained at the desired level.

In the proposed control scheme, the penstock flow is regulated through three longitudinal small sections of pipes as shown in figure. 1. Two pipes are fitted with on/off control valves each having 30% of flow rate under maximum rated load conditions in on state. The third pipe is fitted with a valve which is controlled by a servo motor. The flow rate in the third pipe is continuously controlled by controlling the input signal to the servo motor. It is assumed that as long as the system is in operation a minimum of 10% of maximum load will always be there on the system. Therefore the fourth pipe is without control valve and its size is selected that the flow rate through it is always 10% of the total maximum flow rate. The first or second on/off control valve is either fully open or closed depending upon the loading condition. When the load is less than 40% of the rated maximum load, on/off control valves will remain closed and the servo motor controlled valve will take care of the deviation infrequency due to load variation. Whenever there is disturbance in load, the servo motor controlled valve changes the flow rate so as to maintain the system frequency constant. When the load is between 40% and 70%, one of the on/off control valve will be on and the servo motor controlled valve will operate to maintain the frequency constant. Similarly if the load is between 70% and 100%, both the on/off control valves will be on and the servo motor controlled valve will operate to maintain the frequency constant for load disturbances. The water head is maintained constant by overflow of excess water through spillway and diverting to the fields through a channel for irrigation. This method therefore eliminates the conventional frequency control by additional load management i.e., dump load. The decision of the time for on/off the control valves, when the load increases or decreases plays a vital role in the system dynamics. To study the dynamics, a transfer function model is developed for the system along with the servo motor and on/off controller. Transient responses are shown for different loading conditions and for low, medium and high head installations.

2. SERVO MOTOR VALVE CONTROL

Servo motor control systems are finding widespread applications, mostly in automatic production. This includes nearly all types of packaging machinery, material handling, assembly and other applications including robotics [22]. The programmability feature of servo systems increases its adaptability to different control applications. A very common method of position control using servo motor is by controlling armature voltage and keeping field constant [25, 26]. A servo motor has the advantages of linear speed-torque characteristics, quick response, available at all power ranges [27]. A dc servo motor with armature control for controlling the water flow rate in the penstock and its closed loop transfer function are shown in figure 2. The flow of water is controlled by controlling the position of the valve. The transfer function of dc servo motor is given as [27]:

$$\frac{\theta(s)}{E_a(s)} = \frac{K}{s[L_a J s^2 + (L_a b + R_a J)s + R_a b + KK_b]} \qquad (1)$$

where,

R_a = armature resistance, ohm

L_a = armature inductance, henry

è = angular displacement of the motor shaft, radian

J = equivalent moment of inertia of the motor and load, kg-m2

b = equivalent viscous-friction coefficient of the motor and load, N-m/rad/sec

K = angular velocity and voltage constant in rpm/voltage

K_b = constant

The inductance L_a in the armature circuit is usually small and may be neglected. If L_a is neglected, then the transfer function of (1) is given by:

$$\frac{\theta(s)}{E_a(s)} = \frac{K_v}{s(T_v s + 1)} \qquad (2)$$

where

$K_v = K / (R_a b + KK_b)$ is motor gain constant and (3)

$T_v = R_a J/ (Rab + KK_{b)}$ is motor time constant. (4)

3. SYSTEM DESCRIPTION

Figure.3 shows the transfer function block diagram of an isolated small hydro power system with servo motor and on/off control valves. The model is based on small signal analysis and the rate of increase or decrease of generation by the on/off control valve is therefore taken linear.The first order transfer function is due to delay in measurement or monitoring of the system frequency precedes the servo motor transfer function. The integral gain K_{IS} eliminates the frequency deviations by varying the servo motor valve within limits of minimum and maximum value of limiter 2. As the load increases, frequency will decrease and the servo motor will increase the flow rate to maintain the frequency constant (Äf=0). If $ÄX_S$ reaches the upper limit but frequency deviation is negative, i.e., the frequency is lower than the nominal value, the on/off valve is activated to 'on' position increasing the generation, ÄP$_G$. It is vice versa when the load decreases. The system damping (load frequency characteristics) [28] is given by:

$$D = \frac{P_L^o}{f^o P_R} \tag{5}$$

The system gain constant and time constant are given by

$$K_P = \frac{1}{D} \tag{6}$$

$$T_P = \frac{2H}{f^o D} \tag{7}$$

K$_P$ and T$_P$ will, therefore have different values depending upon loading. P$_R$ is the power capacity of the small hydro power plant.

The time taken by water to travel the penstock under ideal condition is given by

$$t_P = \frac{l}{v} = \frac{l}{\sqrt{2gh}} \tag{8}$$

Where 'l' is the length of the penstock and 'h' is the available head of the water and v is the velocity of water in the penstock. The time constant T$_W$ in the transfer function represent the delay of water in the penstock and is proportional to t$_P$, therefore

$$T_W = kt_P \tag{9}$$

The value of T$_W$ indicates the low, medium or high head installation. The numerator term (zero) in the penstock turbine time constant indicates that the increase or decrease in generation is momentarily opposite when the control valve is opened or closed, respectively, and this effect is more as head increases.

The detail of the control logic is shown in figures. 4(a) and (b). The settling time is used as threshold value for all the switches. Implementation of such control logic is quite possible with low cost analog/digital circuits.

4. SIMULATION, RESULTS AND DISCUSSION

A typical example of an isolated small hydro power system is considered for simulation. The details of the system along with data are given in the Appendix A. If the load ÄP$_L$ varies such that

$0 < P_L^o + \Delta P_L \le 0.4\Delta P_{L,Max}$ or

$0.4P_{L,Max} < P_L^o + \Delta P_L \le 0.7P_{L,Max}$ or

$0.7P_{L,Max} < P_L^o + \Delta P_L \le P_{L,Max}$

only the servo motor controlled valve will vary between minimum and maximum value so as to maintain the frequency constant and there will be no action of the on/off control valves. This is depicted by transient responses, case A (Appendix A) for a step disturbance of $\pm$ 21kW as shown in figure 5. It is observed that the frequency deviations, Äf vanishes in about 200 seconds, and the servo controlled valve attain its new position, ÄX$_S$ as shown in figures 5(a) and 5(b) respectively. Initially when the valve opens to increase the power generation, ÄP$_G$, it decreases first and then increases and vice-versa as shown in figure. 5(c).

For the case B (Appendix A), where the nominal load is $0.7P_{L,Max} < P_L^o \le P_{L,Max}$ and the load disturbance occurs such that $P_L^o + \Delta P_L \le 0.7P_{L,Max}$, the on/off control valve of figure 1 closes to reduce the generation by 0.3P$_{L,Max}$. The transient frequency responses of the system for different step change in load are shown in figure 6. It is observed that a positive steady state error exists in frequency if no corrective action is taken. After 125sec occurrence of the disturbance, valve 1 of the on/off control begins to close to reduce the generation. The time to start corrective action is taken as 125 sec in the simulation, but in practice it may be less and can be considered to start when the steady state error persists within certain range. A sudden decrease in frequency is observed and the servomotor starts increasing the generation. The value of the negative frequency deviation depends on the size of the load disturbance. After that a steady state error exists in frequency as long as the on/off control valve is closing and the servomotor control valve is chasing to open. Finally the servomotor controlled valve opens to the desired level and eliminates the frequency deviation, ÄF=0, when on/off control valve completely closes. The effect of the integrator and proportional gains of the servomotor controller on the transient system frequency responses are shown in figures 7 and 8, respectively. It is observed that the increase in the value of integrator gain, K$_{IS}$ reduces the negative steady state error in frequency but increase the negative peak value and vice-versa, but the settling time almost remains the same. It is also observed that the increase in the value of proportional gain K$_{PS}$ makes the system more oscillatory but reduces the negative peak of frequency response and vice-versa.

The closing time of the on/off valve has considerable effect on the transient responses of the system as shown in figure 9 for step load, ÄP$_L$ = -21kW. The transient responses of system frequency, ÄF$_S$, on/off control valve position, ÄX$_{on/off}$, servomotor control valve position ÄX$_S$ and turbine power generation ÄP$_G$ are shown in figures 9(a)-(d), respectively. It is concluded that rapid closing of the on/off control valve results in large deviation in frequency and power generation but reduces the settling time of the oscillations. On the other hand, the slow closing of the on/off control valve reduces fluctuations in the system frequency and power generation but increases the settling time of the responses.

The closing rate of the on/off control valve has considerable influence on the transient response of the system. Transient responses for initial high rate of closing and subsequent slow rate of closing of the on/off control valve are shown in figures 10 and 11. Comparing the transient responses of the system frequency it is observed from figures 6, 10, and 11 that the performance deteriorates if the initial rate of closing of the on/off control valve is high.

Transient responses for initial slow rate of closing and subsequent high rate of closing of the on/off control valve are shown in figures. 12 and 13. Comparing figure. 6, 12 and 13 it is concluded that the transient responses improve by selecting initial slow rate of closing and later on high rate of closing of the on/off control valve.

For the case C (Appendix A), where the nominal load is $0.4P_{L,Max} < P_L^o \le 0.7P_{L,Max}$ and the load disturbance occurs such that $P_L^o + \Delta P_L > 0.7P_{L,Max}$, the on/off control valve 1 of figure 1 opens to increase the generation by $0.3P_{L,Max}$. The transient responses of system frequency, ÄF$_S$, for variation in on/off control valve gain K_G is shown in figure 14. The magnitude of the rate of opening of the on/off control valve is taken same as for the closing of the control valve in figure 6. By taking the magnitude of the rate of opening of the control valve same as for closing the control valve given in figure 11, the transient responses of the system frequency are shown in figure 15. Similarly taking the magnitude of the rate of opening of the control valve same as for closing the control valve given in figure 13, the transient responses of the system frequency are shown in figure 16. It is also concluded from the responses that if the rate of opening of the on/off control valve is initially low and later on high, the transient performance of the system improves.

For the case D (Appendix A), where the nominal load is $0.4P_{L,Max} < P_L^o \le 0.7P_{L,Max}$ and the load disturbance occurs such that $P_L^o + \Delta P_L \le 0.4P_{L,Max}$, the on/off control valve 2 of figure. 1 closes to decrease the generation by $0.3P_{L,Max}$. The transient frequency responses of the system for different step change in load are shown in figure 17.

For the case E (Appendix A), where the nominal load is $P_L^o \le 0.4P_{L,Max}$ and the load disturbance occurs such that $0.4P_{L,Max} < P_L^o + \Delta P_L \le 0.7P_{L,Max}$, the on/off control valve 2 of figure 1 opens to increase the generation by $0.3P_{L,Max}$. The transient frequency responses of the system for different step change in load are shown in figure 18. The conclusions made for case B and C are applicable to case D and E respectively.

The transient responses shown in figures 5 to 18 are for high head installations i.e., $T_W = 4.0$ sec. The influence of T_W (head) on the transient performance of the system (Case B) has been investigated. The settling time of the responses remaining same for step disturbance of +21kW and for different T_W, as shown in figure 19. For low head installations the peak value of the frequency deviations reduces marginally. Also the momentary opposite frequency deviations due to opening of the valve reduces with reduction in T_W. Therefore the hydro plants of low head installations are more stable than the high head installations. The step deviation in frequency of $\pm$ 1.5 Hz occurs during switching in or off of the control valve and the peak deviation in frequency depends upon the valve of the load disturbance. The cost of the existing and proposed system for various conditions is discussed in detail in appendix B.

5. FIGURES AND TABLES

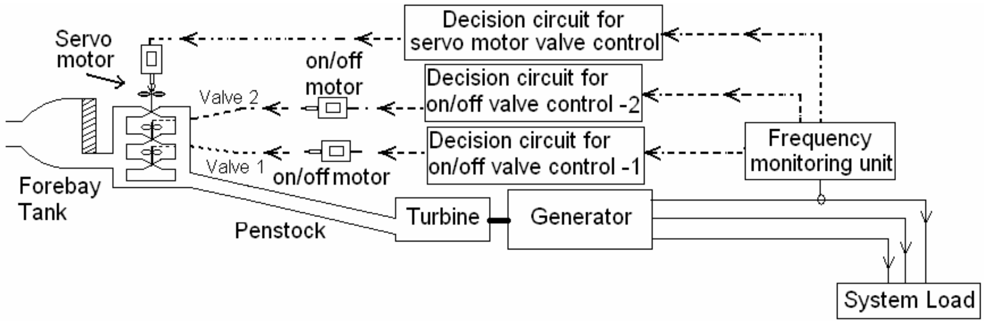

Fig. 1. Proposed scheme of pipes equipped with on/off and servo motor control valves.

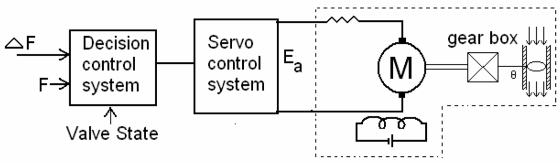

Fig. 2(a). Principal schematic of servo control valve.

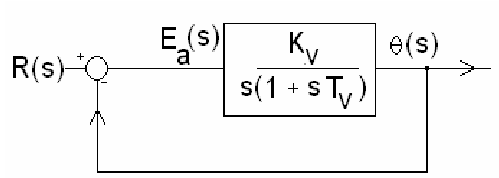

Fig. 2(b). Closed loop transfer function for servo motor valve control.

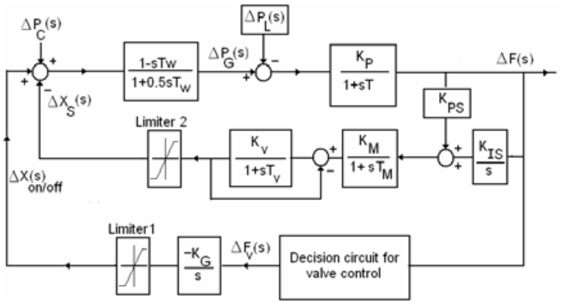

Fig. 3. Transfer function block diagram of small- hydro power system with on/off and servo motor valve controls.

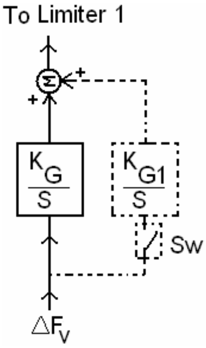

Fig. 4(b). Integrator (dual) for on/off control valve.

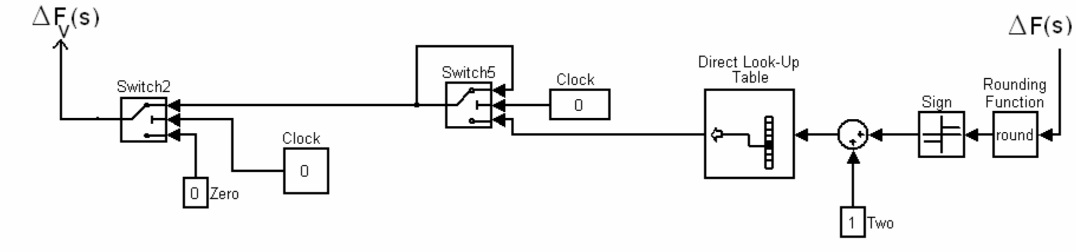

Fig. 4(a). Decision making system for on/off control valve.

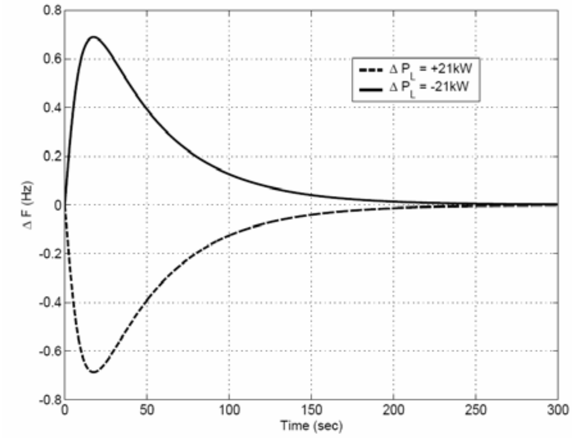

Fig. 5(a). Case A. Transient response of frequency deviation ÄF for various ÄP$_1$.

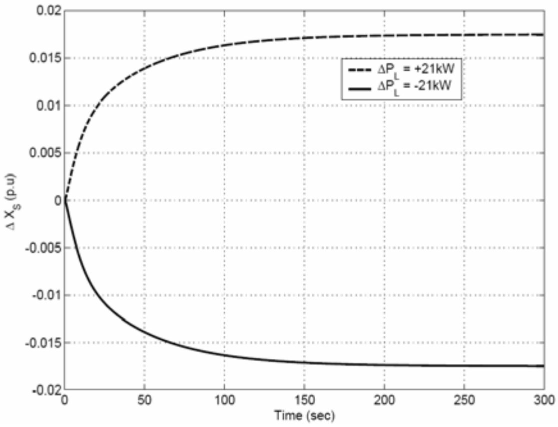

Fig. 5(b). Case A: Transient response showing valve deviation ÄX$_S$ for various ÄP$_1$.

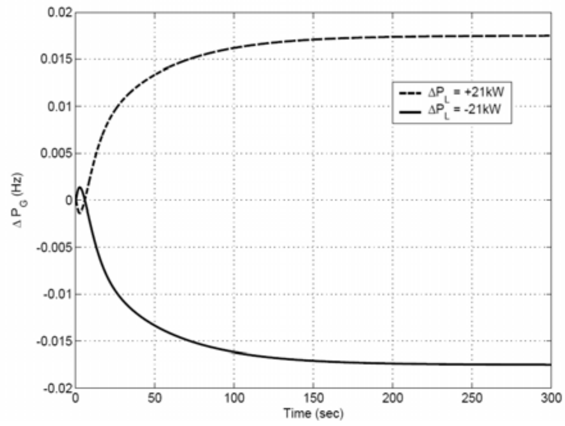

Fig. 5(c). Case A. Transient responses of power generation, ÄP$_G$ for various ÄP$_1$.

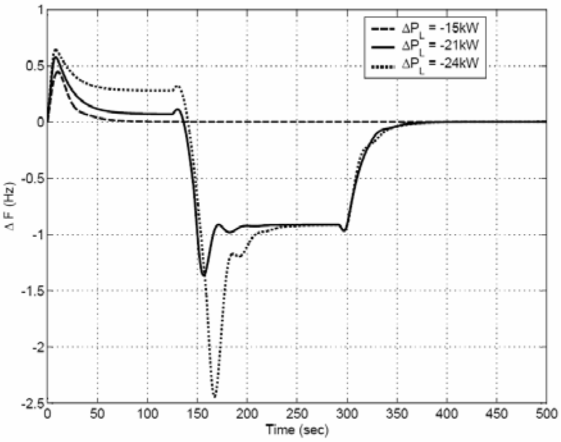

Fig. 6 Case B. Transient response of frequency deviation ÄF for various ÄP$_L$.

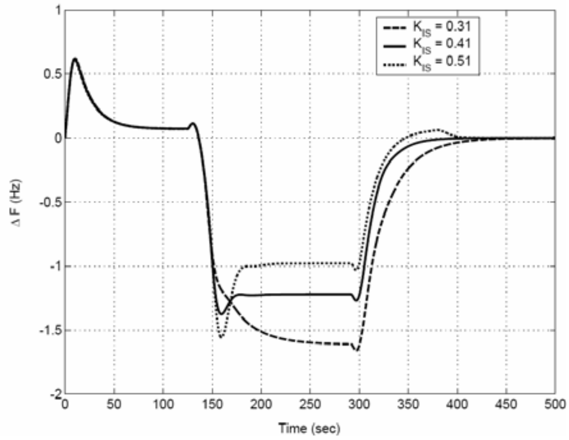

Fig. 7 Case B. Transient responses of frequency deviation ÄF for variation in K_{IS}, for fixed ÄP_L (21kW).

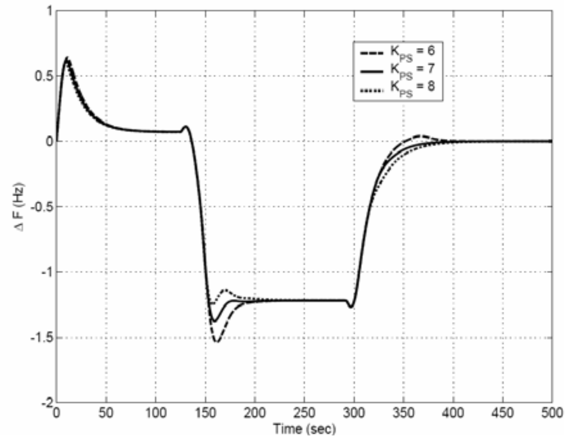

Fig. 8 Case B. Transient responses of frequency deviation ÄF for variation in K_{PS}, for a fixed ÄP_L (21kW).

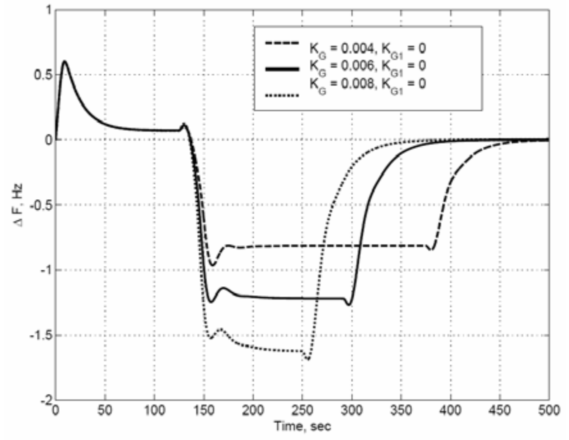

Fig. 9(a) Case B. Transient responses of frequency deviation ÄF for variation in K_G, for a fixed ÄP_L (21kW).

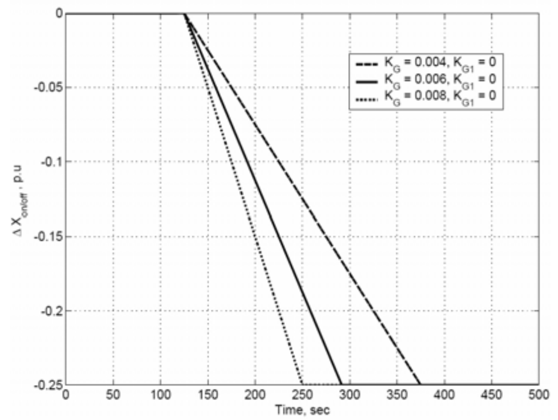

Fig. 9(b) Case B. Transient response of the on/off valve position, Ä$X_{on/off}$ for variation in K_G, for a fixed ÄP_L (21kW).

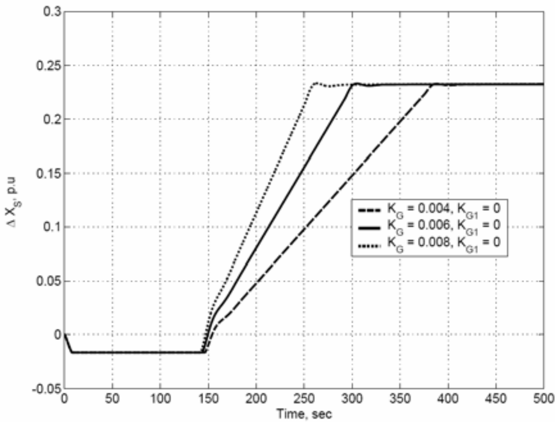

Fig. 9(c) Case B. Transient response of the servo motor controlled valve position, ÄX_S, for variation in K_G, for a fixed ÄP_L (21kW).

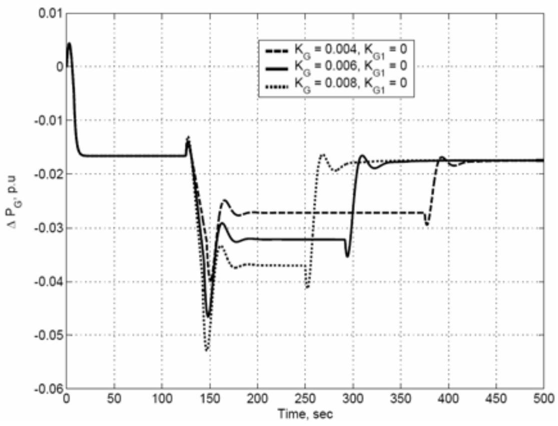

Fig. 9(d) Case B. Transient responses of power generation, ÄP_G system for different rate of closing of on/off control valve, K_G for a fixed ÄP_L (21kW).

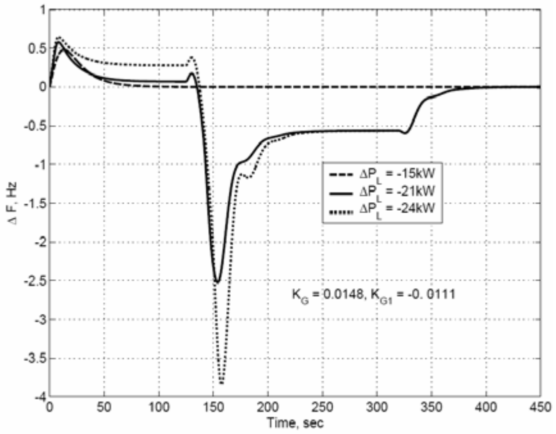

Fig. 10. Case B. Transient responses of frequency deviation ÄF, for various loads ÄP$_{L,}$ with initial high rate of closing of the on/off valve.

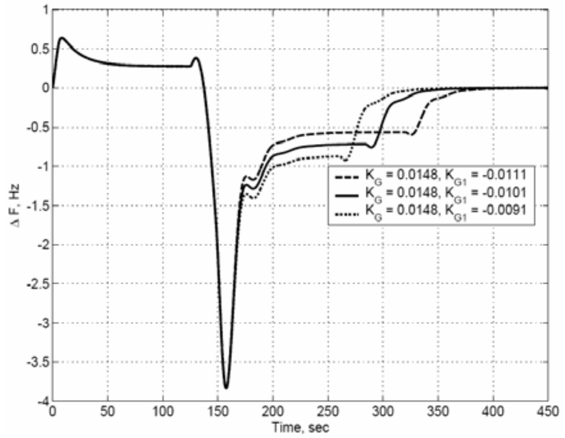

Fig. 11. Case B. Transient responses of frequency deviation ÄF for different K$_{G,}$ for a fixed ÄP$_L$ (21kW).

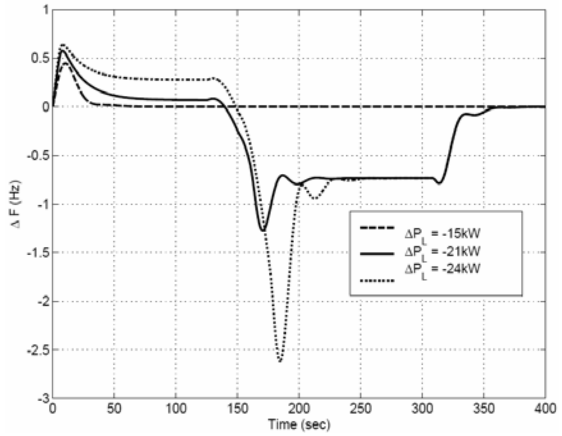

Fig. 12. Case B. Transient responses of frequency deviation ÄF, for various loads ÄP$_{L,}$ with initial low rate of closing of the on/off valve.

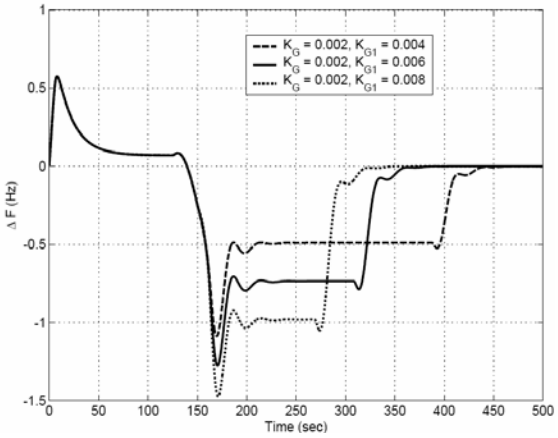

Fig. 13. Case B. Transient responses of frequency deviation ÄF for different K$_{G,}$ for a fixed ÄP$_L$ (21kW).

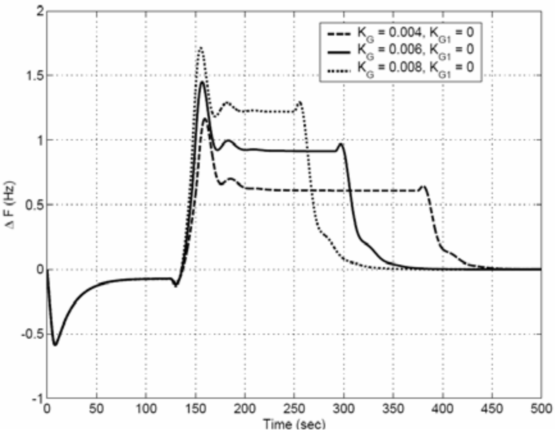

Fig. 14. Case C. Transient responses of frequency deviation ÄF for variation in K$_G$, for a fixed ÄP$_L$(21kW).

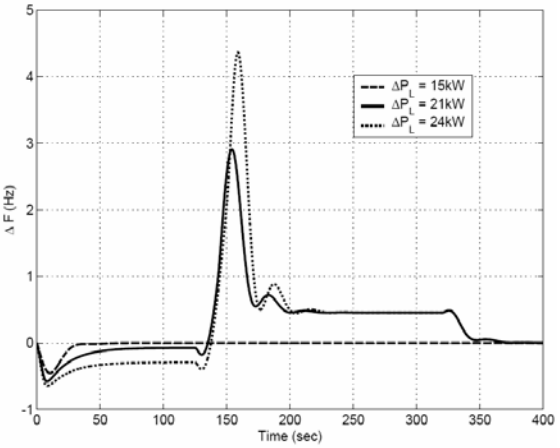

Fig. 15. Case C. Transient responses of frequency deviation ÄF for various loads ÄP$_L$ with initial high K$_G$.

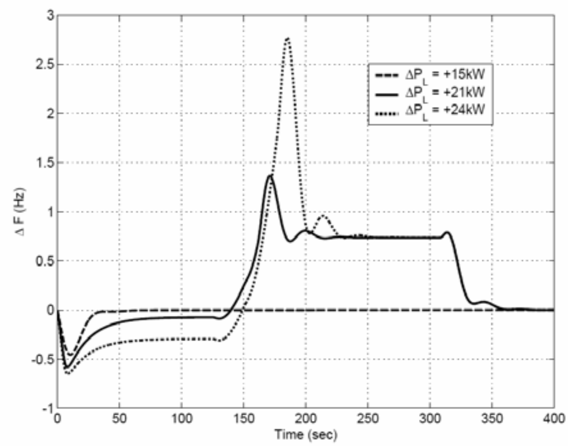

Fig. 16. Case C. Transient responses of frequency deviation ÄF for various loads ÄP$_L$ with initial low K$_G$.

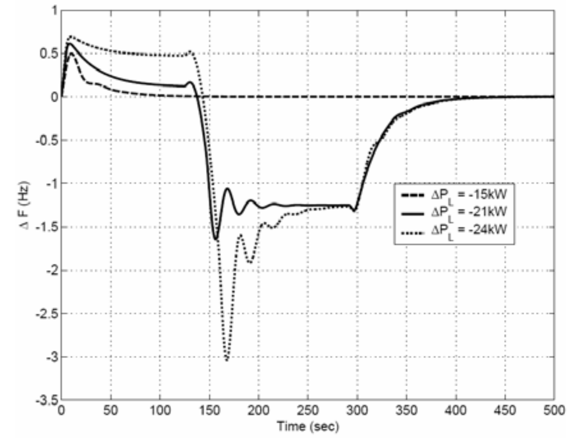

Fig. 17. Transient responses of system Case D for step changes in load, ÄP$_{L,}$ showing deviations in frequency, ÄF.

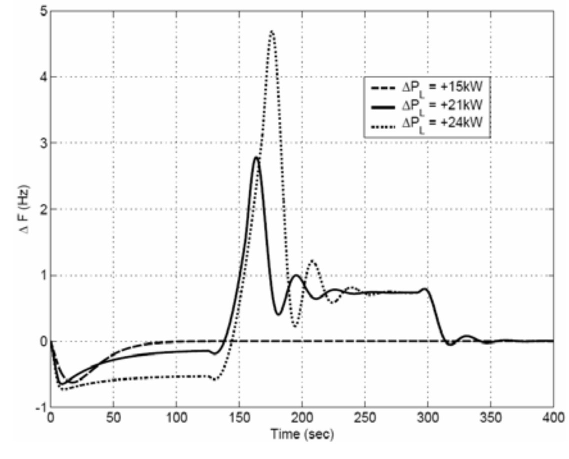

Fig. 18. Case E. Transient responses of frequency deviation ÄF for various loads ÄP$_L$.

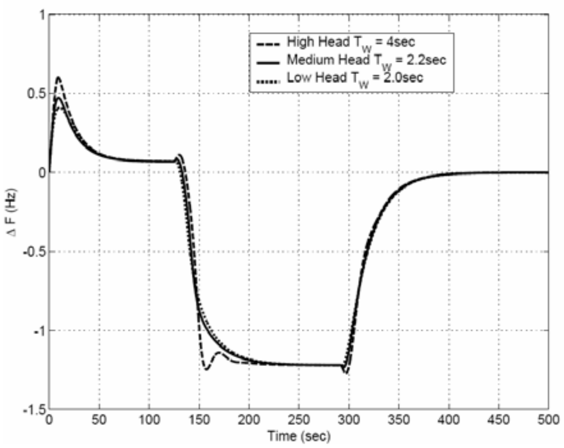

Fig. 19. Transient responses of system case B for step change in load, ÄP$_L$ (+21kW) for various changes in head (T$_W$), showing deviations in frequency, ÄF.

6. CONCLUSIONS

A new method of automatic frequency control of an isolated small hydro power plant is proposed to eliminate the conventional dump load controller. It is very important as the saved water can be used for irrigation which is the primary need of the local community for their survival. It is observed that the new technique effectively eliminate the frequency deviations due to load disturbances for different nominal loadings of the system. From simulation results it is clear that the system is more dynamically stable if the on/off control valve has rate of closing or opening initially low and later on high. Some of the system transient responses due to step disturbances are shown for different nominal loadings and controller gains. Finally with the proposed method, the cost of the controllers including valves is considerably less than the dump load cost (Appendix B), in addition to saving water for irrigation.

7. Nomenclature

K_M	Error and measuring circuit gain constant
Kp	power system gain constant, Hz/p.u.
H	inertia constant of the generation system, sec
p.u	per unit of power
K_G	integral gain constant for on/off control valve
K_v	gain constant for servo system
K_{PS}	proportional gain controller constant for servo system
K_{IS}	Integral gain constant for servo system
T_M	Time taken for measuring data, sec
T_P	power system time constant, sec

T_v	Servo motor time constant, sec
T_w	nominal starting time of water in penstock, sec
ÄF	frequency deviation, Hz
ÄP_G	change in generation, p.u
ÄP_L	change in load, p.u
ÄX_S	change in servo motor controlled valve position, p.u
Ä$X_{on/off}$	change in on/off control valve position, p.u

8. APPENDIX

Appendix A

Ratings and the data of the typical example of isolated power system studied.
Capacity if the small hydro power plant,

P_R = 1200 kW

Maximum Nominal load on the system,

$P_{L,Max}$ = 1000kW

Continuous flow = 100kW

System nominal frequency, f^o = 50 Hz

Inertia constant of the generator, H = 5 sec
Time constants:

T_M = 0.02 sec,
T_V = 0.1 sec
T_W = 1.0 sec (low head), 2.2 sec (medium head), and 4.0 sec (high head)

Gain Constants:

K_M = 0.004, K_V = 2.5, K_{IS} = 0.41 and K_{PS} = 7.0

Table. A.1. Five Possible Cases for Four Pipe Three Valve Control

case	N.L	D	K_p	T_p	O_{C1}	O_{C2}	S_C	O_{CL}	S_{CL}
A	0.75	0.015	66.67	13.333	(Open) 0.25	(Open) 0.25	0.1667	-0.25 to 0	-0.16667 to +0.0833
B	0.6	0.012	83.333	16.667	(Open) 0.25	(Open) 0.25	0.1	-0.25 to 0	-0.01667 to +0.2333
C	0.5667	0.0113	88.235	17.647	(Closed) 0	(Open) 0.25	0.3167	0 to 0.25	-0.2333 to 0.01667
D	0.35	0.007	142.85	28.57	(Closed) 0	(Open) 0.25	0.1	-0.25 to 0	-0.01667 to 0.2333
E	0.3167	0.00633	157.89	31.578	(Closed) 0	(Open) 0.25	0.1	0 to 0.25	-0.2333 to 0.01667

Where,

N.L : Nominal Load in p.u

O_{C1} : On/Off control valve 1, (initial state) in p.u

O_{C2} : On/Off control valve 2, (initial state) in p.u

S_C : Servo motor control valve, initial state in p.u

O_{CL} : On/Off control limiter in p.u

S_{CL} : Servo motor control valve limiter in p.u

Appendix B

The size of pipes/valves for 1000kW power output of the hydro turbine for various heads of water is given in table B.1.

Table B.1. The Diameter of Pipes/Valves for Different Net Head of Water

S.no	h (m)	Q (m^3/sec)	d (mm) at 100% q	d1 (mm) at 30% q	d2 (mm) at 10% q
1	10	13.333	1095.6	600.1	346.5
2	20	6.667	651.5	356.8	206
3	50	2.667	327.7	179.5	103.6
4	100	1.333	194.8	106.7	61.6
5	200	0.667	115.9	63.5	36.6

Where $P_o = \eta q g h$

P_o is the turbine output power in kW,
ç is the efficiency of turbine (0.75),
q is the flow rate (m^3/sec),
h is the net head (m),
q = Area of the pipe x Velocity,

Velocity of water = $\sqrt{2gh}$,
d1 = diameter of the three pipe (mm)
d2 = diameter of fourth pipe (mm)
d = diameter of the incoming pipe (mm)

The cost of sluice gate/valve is given in table B.2

Table B.2. Approximate Cost of Sluice Gates/Valves

Pipe diameter (mm)	Approximate cost (Indian Rupees)
1000	2,50,000 to 3,30,000
500	35,000 to 50,000
250	6,000 to 8,000
100	600 to 1000

The cost of smaller size sluice gates/valve is considerably less as they are readily available due to their large consumption. The cost of control (motor + sensor+ electronic circuit etc) depends upon the type, accuracy and complexity. It varies from 25% to 80% of the cost of sluice gate/valve.

The cost of 1000kW dump load (water heater system) with controls is approximately Rs 10,00,000 to Rs 15,00,000.

It is very clear from the above prices; the cost of proposed system is cheaper than the existing dump load compensation. In addition to lesser price, the proposed system saves water for irrigation.

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