Load Frequency Control of an Isolated Small-Hydro Power Plant With Reduced Dump Load

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***Abstract*—In this paper, a novel technique for load frequency control of an isolated small-hydro plant is presented. In general, the frequency is controlled by using a dump load, whose rating is equal to the rated power output of the plant. The new scheme proposed reduces the size of the dump load by controlling input power of the hydro power plant using on/off controls. The water flowing through the penstock is rerouted in smaller pipes, two or three fitted with motor operated valves. The opening or closing of the valves is achieved by on/off controls. The on/off control linearly raises or lowers the generation. A generalized transfer function model for the system is developed with an on/off control logic. Finally, the transient performance of the system is compared for the two-pipe case (50% dump load) and the three-pipe case (30% dump load).**

***Index Terms*—Dump load, generation control, on/off control.**

NOMENCLATURE

H	Inertia constant of the generation system (s).
p.u.	Per unit of power.
K_D	Dump load firing circuit gain constant.
K_{ID}	Integral gain constant for dump load.
K_P	Power system gain constant (Hz/p.u.).
MPFC	Multi Pipe Flow Control.
T_P	Power system time constant (s).
T_w	Nominal starting time of water in penstock (s).
T_α	Dump load firing circuit time constant (s).
T_M	Time taken for measuring data (s).
ΔF	Frequency deviation (Hz).
ΔP_G	Change in generation (p.u.).
ΔP_L	Change in load (p.u.).
ΔP_D	Dump load deviation (p.u.).

I. INTRODUCTION

SMALL-HYDRO power generation plays a vital role in rural electrification in the case of developing countries [1]–[3]. The reason for tapping the local available small-hydro sources [2]–[4] are as follows.

- There is a low gestation period with minimum maintenance as no heat is involved.
- It is a nonpolluting source of energy.
- No long transmission network is required; therefore, network cost is reduced with increase in reliability and no transmission losses.
- The starved national grid is not able to meet the connected load; instead, the gap between supply and demand is increasing day by day.

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 [3], [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 [5].

The system frequency can be maintained constant by eliminating the mismatch between generation and load. A conventional speed governor with supplementary integral control is generally used to maintain the frequency constant both for grid connected and isolated mode operation [5], [6]. In general, the generation control mechanism is not used for small-hydro plants due to prohibitively high cost; therefore, frequency is maintained by load management. In a stand-alone small-hydro generation, the rated power is always generated subject to the availability of the source. Any variation in power demand is controlled by a resistive load called dump load. The dump load is a thyristor controlled heater load so that the actual load plus dump load is equal to the power generated at rated frequency [7]–[9]. The system is proved to be cost effective when there is a hot water requirement. A PI controller generally is used with a six-pulse firing angle control technique for elimination of frequency fluctuations [10]–[14]. A special case of dump load is reported, which consists of eight three-phase resistors (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 [15]–[17].

II. PROPOSED MPFC SYSTEM

The generalized block diagram of the proposed system is shown in Fig. 1(a). The proposed system can be categorized into two ways. The first one is a two-pipe control, and the second is a three-pipe control. In the case of two-pipe control, a small section of penstock employs two pipes of equal diameter, one fitted with a control valve, as shown in Fig. 1(b). The water flow rate is equal in both the pipes when the control valve is fully open. The control valve is either fully open or closed, depending upon the loading condition. If the valve is fully closed, the flow rate

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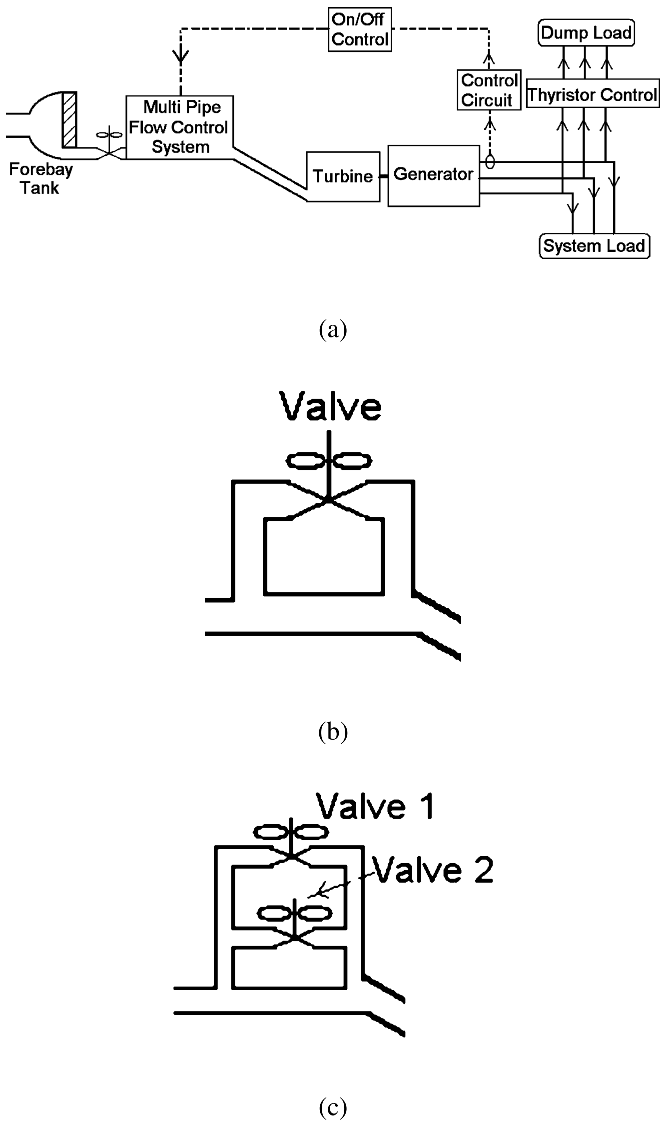


(a)

(b)

(c)

Fig. 1. (a) Proposed system. (b) Two-pipe single-valve control. (c) Three-pipe two-valve control.

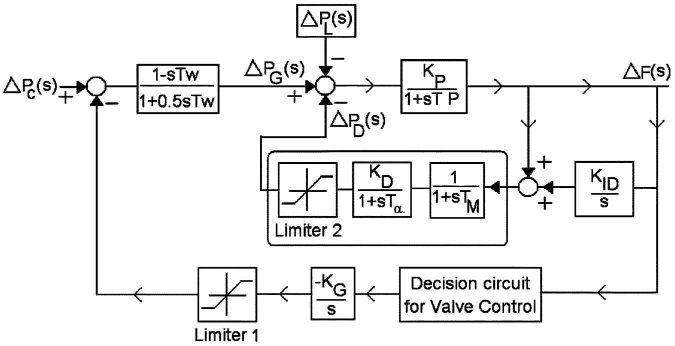


Fig. 2. Block diagram of small-hydro power plant with dump load and on/off valve control.

is reduced to half and hence the power. The water head is maintained constant by overflow of excess water through spillway to the stream. This method reduces the size of the dump load to 50% of the amount normally required.

In the three-pipe system, the penstock flow is regulated through three longitudinal small sections of pipes as shown in Fig. 1(c). Two pipes are fitted with control valves with each pipe having 30% of flow rate under maximum rated load conditions. The third pipe has 40% of the flow rate under all conditions. The role of control valve and maintenance of water head are the same as for the two-pipe case. This method reduces the size of the dump load to 30% of the amount normally required, assuming minimum load of 10% contributing to power house demand and some emergency needs.

The decision of the time for on or off for the control valve, 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 dump load and on/off controller. Transient responses are shown for different operating conditions when the system is subjected to small disturbances.

Fig. 2 shows the transfer function block diagram of an isolated small-hydro power plant with dump load and on/off valve control. The model is based on small signal analysis, and the rate of increase or decrease of generation by the control valve is therefore taken to be linear. The dump load consists of a resistive load with six-pulse control technique. The first-order transfer functions are due to delay in firing of the thyristors and monitoring of the system frequency. The integral gain $\mathrm{K_{ID}}$ eliminates the frequency deviations by varying the dump load from nominal value within limits of minimum and maximum value of limiter2. As the load increases, frequency will decrease and the dump load will also decrease to maintain the frequency constant $(\Delta \mathrm{F} = 0)$.

If $\Delta \mathrm{P_D}$ reaches the lower limit but frequency deviation is negative, i.e., the frequency is lower than the nominal value, the control valve is activated to "on" positio,n increasing the generation $\Delta \mathrm{P_G}$ by 50% and 30% of maximum rated load $(\mathrm{P_{L,Max}})$ in two-pipe and three-pipe control, respectively. It is vice versa when the load decreases. The system damping (load frequency characteristics) [6], [18] is given by

$$D = \frac{\left(P_L^o + P_D^0\right)/P_R}{f^o}. \tag{1}$$

The system gain constant and time constant are given by

$$K_P = \frac{1}{D} \tag{2}$$

$$T_P = \frac{2H}{f^o D}. \tag{3}$$

$\mathrm{K_P}$ and $\mathrm{T_P}$ will therefore have different values (two in two-pipe control and three in three-pipe control), depending upon nominal loading. $\mathrm{P_R}$ is the power capacity of the small-hydro power plant. The velocity of water in the penstock is given by

$$V = \sqrt{2gh}. \tag{4}$$

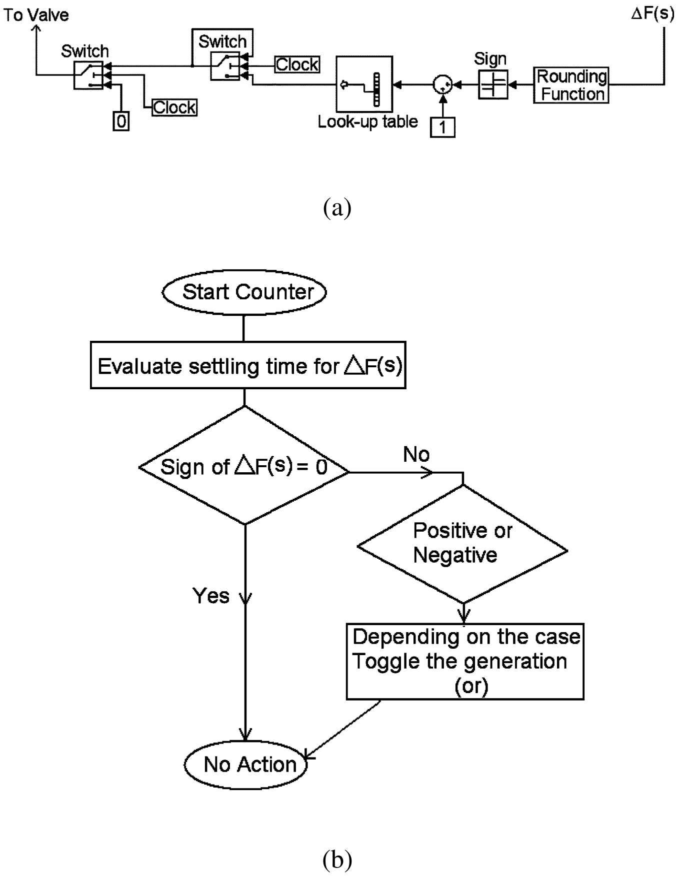


Fig. 3. (a) Decision-making system for on/off valve control. (b) Flow chart for on/off control of the valve.

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

$$t_P = \frac{l}{\sqrt{2gh}} \tag{5}$$

where l is the length of the penstock, and h is the available head of the water (also $\mathrm{l > h}$). $\mathrm{T_W}$ represents the delay of water in the penstock and is proportional to $\mathrm{t_P}$; therefore

$$T_W = kt_P. \tag{6}$$

The value of $\mathrm{T_W}$ lies between 0.5 and 4.0 s, depending upon the head (low, medium, or high). The numerator term (zero) in the penstock turbine transfer function indicates the increase or decrease in generation is momentarily opposite when the control valve is opened or closed, respectively. The effect is more as head increases.

The details of the control logic are shown in Fig. 3(a), and the functional flow chart of the input valve controller is given in Fig. 3(b).

The settling time is passed as the threshold value for all the switches. Implementation of such control logic is quite possible with low-cost analog/digital circuits.

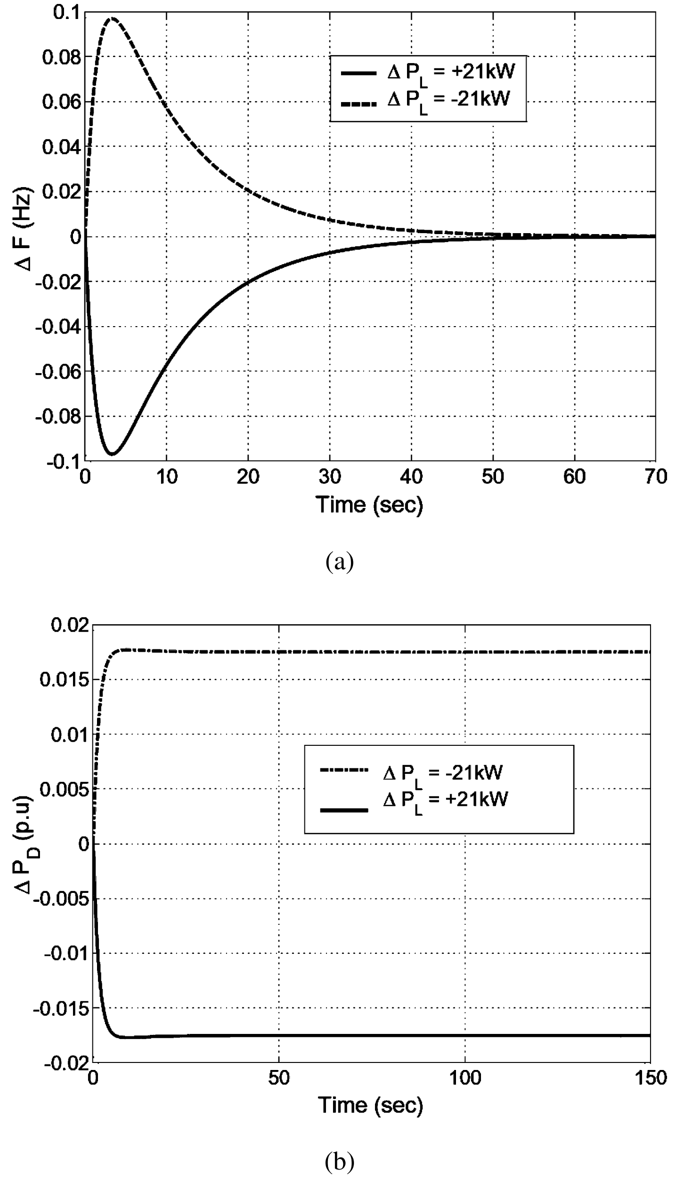


Fig. 4. (a) Case A1.1: transient response of $\Delta\mathrm{F}$ for various step changes in load $\Delta\mathrm{P_L}$. (b) Case A1.1: dump load response $\Delta\mathrm{P_D}$ for various step changes in load $\Delta\mathrm{P_L}$.

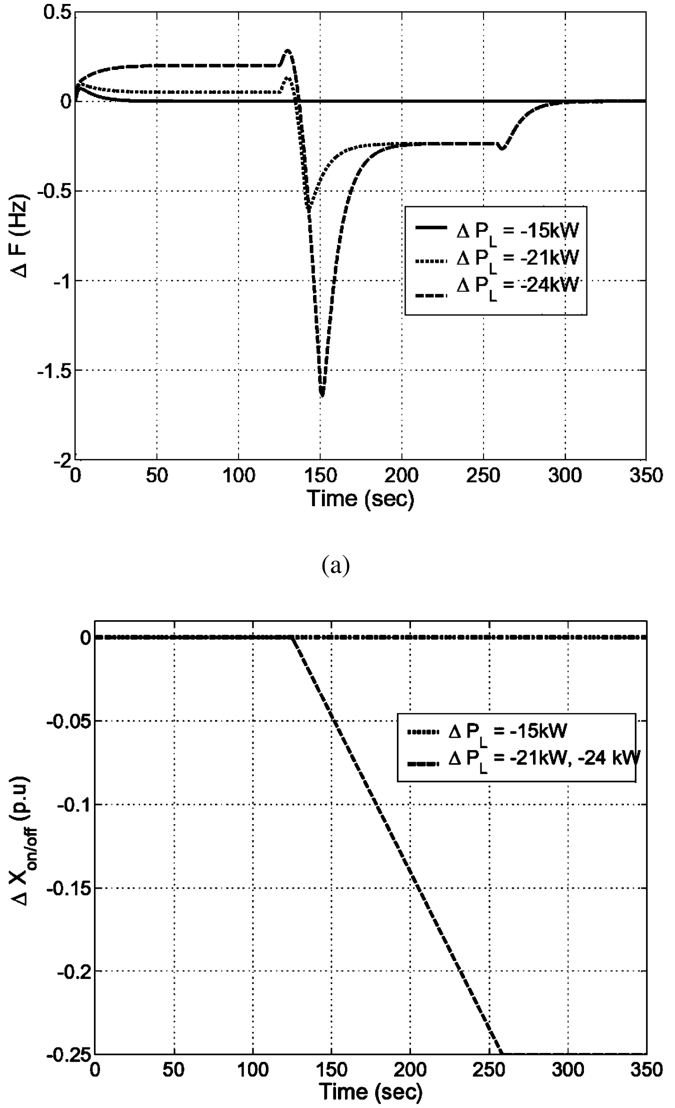
III. SIMULATION RESULTS AND DISCUSSION

A. Two-Pipe Control

A typical example of an isolated small-hydro power plant is considered for simulation (see the Appendix). The details of the system along with data are given in Appendix A.1. If the load $\Delta\mathrm{P_L}$ varies such that

$$0 \le P_L^o + \Delta P_L \le 0.5P_{L,Max} \text{ or}$$
$$0.5P_{L,Max} \le P_L^o + \Delta P_L \le P_{L,Max}$$

only the dump load will vary between minimum and maximum value so as to maintain the frequency constant, and there will be no action of the control valve. This is depicted by transient responses of the system case A1.1 (see Appendix A1) for a step disturbance of ±21 kW, as shown in Fig. 4. It is observed that



(a)

(b)

Fig. 5. (a) Case A1.2: transient response of $\Delta\mathrm{F}$ for various step changes in load $\Delta\mathrm{P_L}$. (b) Case A1.2: transient response of $\Delta\mathrm{Xon/off}$ for various step changes in load $\Delta\mathrm{P_L}$.

the frequency and dump load deviations $\Delta\mathrm{F}$ and $\Delta\mathrm{P_D}$ vanish in about 60 s.

When the nominal load $P_L^o > 0.5\mathrm{P_{L,Max}}$ and the load disturbance occurs such that $P_L^o + \Delta P_L \le 0.5P_{L,Max}$, then the control valve closes to reduce the generation by 50%. The transient responses of system case A1.2 (see Appendix A1) for different step disturbances are shown in Fig. 5. As the load decreases (-21 and -24 kW), the frequency increases, and it attains a steady-state value in about 50 s. The control logic circuits start closing the valve at about 125 s; therefore, the frequency momentarily increases and then decreases sharply to a new steady-state value and remains constant from 200 to 260 s. The steady-state error in frequency is eliminated by the control action of the dump load, i.e., $\Delta\mathrm{F}$ vanishes in about 300 s. For a 15-kW decrease in load, only the dump load manages the frequency deviation $\Delta\mathrm{F}$ to vanish.

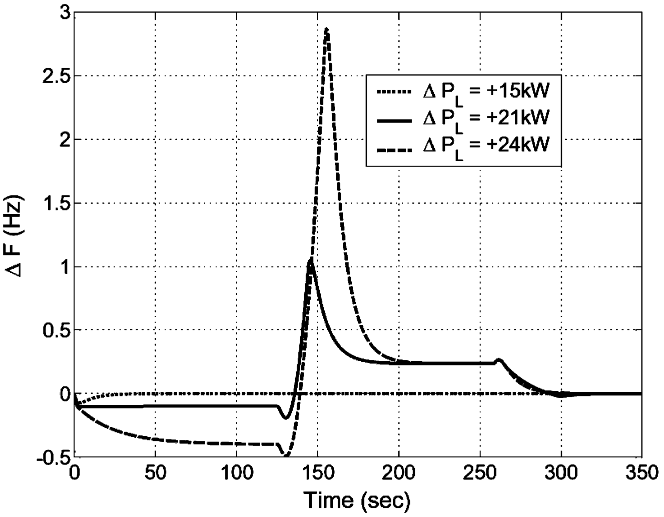


Fig. 6. Case A1.3: transient response of $\Delta\mathrm{F}$ for various step changes in load $\Delta\mathrm{P_L}$.

When the nominal load $P_L^o \le 0.5P_{L,Max}$ and the load disturbance occurs such that $P_L^o + \Delta P_L > 0.5P_{L,Max}$, then the control valve opens to increase the generation by 50%. The transient responses of such system case A1.3 (see Appendix A1) for different step disturbances are shown in Fig. 6. The comparison of the transient responses (see Figs. 5 and 6) shows that the settling time of the responses is the same for both cases. The peak of the frequency deviation is considerably more in case A1.3 compared to case A1.2. The reason is that the nominal value of the dump load was small when transition occurred in case A1.3, whereas it was very high in case A1.2, which controls the peak deviation in frequency.

B. Three-Pipe Control

The details of this system along with data are given in Appendix (A.2). If the load $\Delta\mathrm{P_L}$ varies such that

$$\begin{aligned}
0.1P_{L,Max} &< P_L^o + \Delta P_L \le 0.4P_{L,Max} \quad \text{or}\\
0.4P_{L,Max} &< P_L^o + \Delta P_L \le 0.7P_{L,Max} \quad \text{or}\\
0.7P_{L,Max} &< P_L^o + \Delta P_L \le P_{L,Max}
\end{aligned}$$

only the dump load will vary between minimum and maximum value so as to maintain the frequency constant, and there will be no action of the control valve. This is depicted by transient responses of the system case A2.1 (see Appendix A2) for a step disturbance of ±21 kW, as shown in Fig. 7. It is observed that the frequency deviations $\Delta\mathrm{F}$ vanish in about 65 s.

For the system case A2.2 (see Appendix A2), where the nominal load is $P_L^o > 0.7\mathrm{P_{L,Max}}$ and the load disturbance occurs such that $0.4P_{L,Max} \le P_L^o + \Delta P_L \le 0.7P_{L,Max}$, the control valve 1 closes to reduce the generation by 30%. The transient responses of such a system for different step disturbances in load are shown in Fig. 8. As the load decreases (-21 and -24 kW), the frequency increases, and it attains a steady-state value in about 65 s. The control logic circuits start closing the valve at about 125 s; therefore, the frequency momentarily increases and then decreases sharply to a new steady-state value

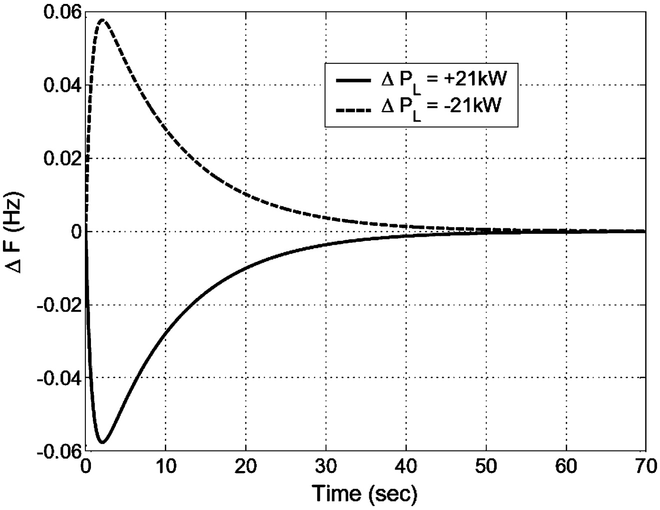


Fig. 7. Case A2.1: transient response of $\Delta \mathrm{F}$ for various step changes in load $\Delta \mathrm{P_L}$.

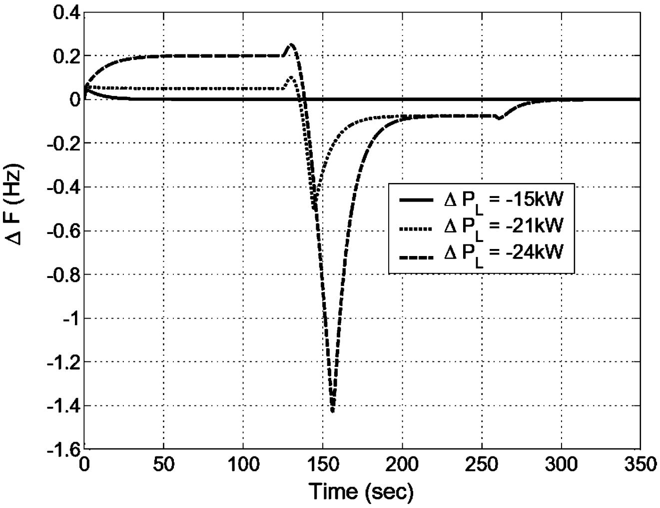


Fig. 8. Case A2.2: transient response of $\Delta \mathrm{F}$ for various step changes in load $\Delta \mathrm{P_L}$.

and remains constant from 200 to 260 s. The steady-state error in frequency is eliminated by the control action of the dump load, and $\Delta \mathrm{F}$ vanishes in about 300 s. For a 15-kW decrease in load, only the dump load manages the frequency deviation $\Delta \mathrm{F}$ to vanish.

For the system case A2.3 (see Appendix A2), where the nominal load $0.4P_{L,Max} < P_L^o \leq 0.7P_{L,Max}$ and the load disturbance occurs such that $P_L^o + \Delta P_L > 0.7P_{L,Max}$, then the control valve 1 opens to increase the generation by 30%. The transient responses of such a system for different step disturbances are shown in Fig. 9. The peak of the frequency deviation considerably more in case A2.3 compared to case A2.2. The reason is the same as mentioned in the two-pipe control case.

For the system case A2.4 (see Appendix A2), where the nominal load is $0.4P_{L,Max} < P_L^o \leq 0.7P_{L,Max}$ and the load disturbance occurs such that $P_L^o + \Delta P_L \leq 0.4P_{L,Max}$, the control valve 2 closes to reduce the generation by 30%. (For the case A2.4 and A2.5, valve-1 is closed.) The transient responses of such a system for different step disturbances in load are shown in Fig. 10.

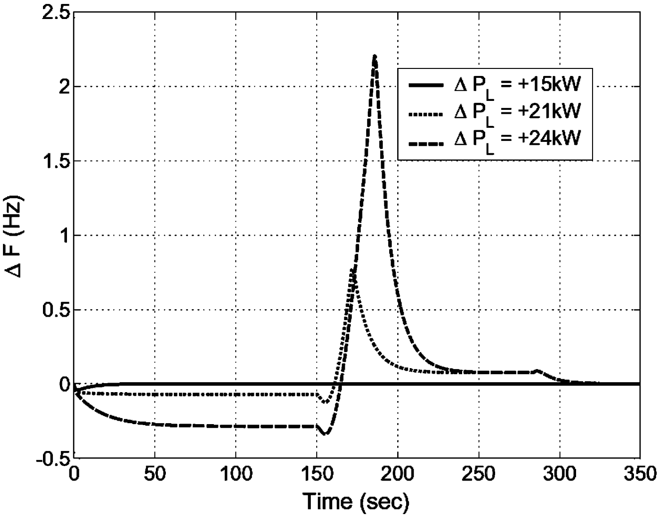


Fig. 9. Case A2.3: transient response of $\Delta \mathrm{F}$ for various step changes in load $\Delta \mathrm{P_L}$.

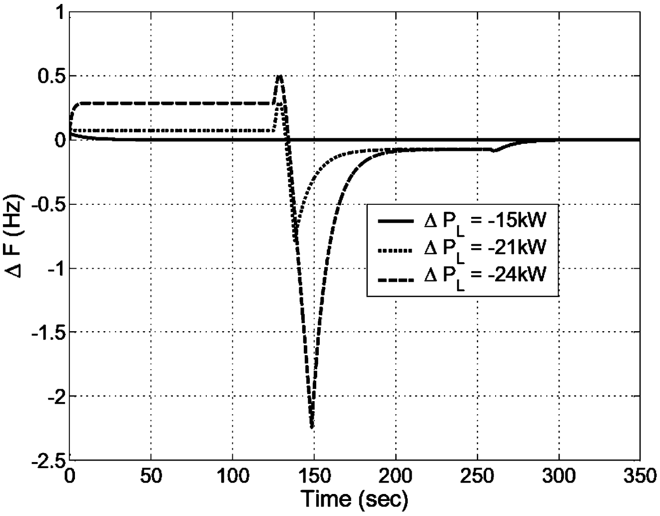


Fig. 10. Case A2.4: transient response of $\Delta \mathrm{F}$ for various step changes in load $\Delta \mathrm{P_L}$.

For the system case A2.5 (see Appendix A2), where the nominal load $P_L^o \leq 0.4P_{L,Max}$ and the load disturbance occurs such that $0.4P_{L,Max} \leq P_L^o + \Delta P_L \leq 0.7P_{L,Max}$, then the control valve 2 opens to increase the generation by 30%. The transient responses of such a system for different step disturbances are shown in Fig. 11.

The peak deviation in frequency of ±2 to 3 Hz occurs during switching on or off of the control valve. The duration of the deviation is very small, and the peak in frequency deviation can be reduced by proper selection of $\mathrm{K_G}$ and $\mathrm{K_{ID}}$. Comparing the responses show in Figs. 4 and 7, it has been observed that the transient performance of the three-pipe system is better than the two-pipe system.

The toggling of the valves can occur if the load oscillates above and below the critical load point. The rapid switching of valves can cause more wear and tear on the turbine system. The

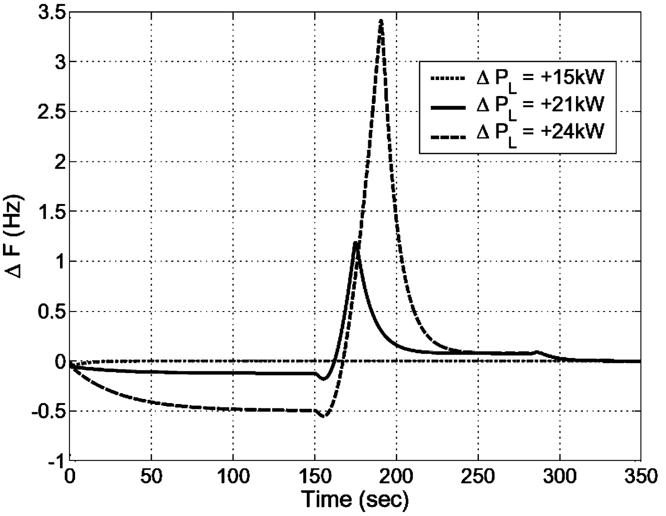


Fig. 11. Case A2.5: transient response of ΔF for various step changes in load ΔP_L.

value of the switching in and out of the small load causing frequent toggling and its time of occurrence can be assessed from the daily load flow curve of the system. Therefore, a small local load equivalent to the above assessed load is required, which by switching in raises the load on the system above the critical load point and avoids toggling. Fast consecutive on/off occurrences can be sensed by a very simple electronic circuit that switches in this small equivalent load for a given interval of time. The size of the equivalent small load and the time interval for which it is to be on are purely site specific.

IV. CONCLUSIONS

A new method of frequency control of an isolated small-hydro power plant that reduces the rating of the dump load by 50% and/or 30% of the nominal value has been investigated by using an on/off control valve. The control valve linearly switches in or out 50% or 30% of the total generation as required by the load. A transfer function model of the system has been developed. To investigate the transient performance of the system, various cases of the typical system were considered. It has been observed that the transient responses of the system due to a step disturbance settle in 60 to 65 s, if it is controlled by a dump load alone. If there is a switching in or switching out of the control valve along with the dump load, it has been found that the transient response of the system settles in 300 s with $\Delta F = 0$. Therefore, the proposed scheme is very effective in frequency control of the small-hydro system in addition to reduction in the size of the dump load by 50% and/or 30%, and also, the cost of the controllers including valves is considerably less than the dump load cost (see Appendix B), in addition to saving water.

APPENDIX A

Ratings and the data of the typical example of isolated power plant studied:

TABLE I
POWER SYSTEM CONSTANTS

Operating Load (kW)	$P_L^o + P_D^o$ kW	D	K_p	T_p
> 500kW	1000	0.01667	60	12
< 500kW	500	0.00833	120	24

TABLE II
TYPICAL LOADINGS AND LOWER AND UPPER LIMITS OF THE LIMITERS

Case	Initial Load (p.u)	Dump load (p.u)	Limiter 1 (p.u)	Limiter 2 (p.u)
A1.1	0.75	0.0833	-0.41667 to 0	-0.833 to 0.333
A1.2	0.433	0.4	-0.41667 to 0	-0.4 to 0.0167
A1.3	0.4	0.01667	0 to 0.4167	-0.1667 to 0.4

TABLE III
POWER SYSTEM CONSTANTS

Operating Load (kW)	$P_L^o + P_D^o$ kW	D	K_p	T_p
> 700	1000	0.01667	60	12
400<P_L<700	700	0.011667	85.71	17.14
< 400	400	0.00667	150	30

Capacity of the small-hydro power plant, $P_R = 1200$ kW
Maximum nominal load on the system, $P_{L,Max} = 1000$ kW
System nominal frequency, = 50 Hz
Inertia constant of the generator, $H = 5$ s

Time constants:

$$
\begin{aligned}
T_M &= 0.02\ \text{s},\ T_\alpha = 0.05\ \text{s} \\
T_W &= 1.0\ \text{s (low head system)} \\
T_W &= 2.2\ \text{s (medium head system)} \\
T_W &= 4.0\ \text{s (high head system)}
\end{aligned}
$$

Gain Constants:

$$
\begin{aligned}
K_{PD} &= 1.0 \\
K_{ID} &= 0.1 \\
K_G &= 0.0075
\end{aligned}
$$

A. Two-Pipe Control

The power system constants are shown in Table I, and the typical loadings and lower and upper limits of the limiters are shown in Table II.

B. Three-Pipe Control

The power system constants are shown in Table III, and the typical loadings and lower and upper limits of the limiters are shown in Table IV.

TABLE IV
TYPICAL LOADINGS AND LOWER AND UPPER LIMITS OF THE LIMITERS

Case	Initial Load (p.u)	Dump load (p.u)	Limiter 1 (p.u)	Limiter 2 (p.u)
A2.1	0.75	0.0833	-0.25 to 0	-0.833 to 0.1667
A2.2	0.6	0.233	-0.25 to 0	-0.233 to 0.01667
A2.3	0.5667	0.01667	0 to 0.25	-0.01667 to 0.233
A2.4	0.35	0.2333	-0.25 to 0	-0.233 to 0.01667
A2.5	0.31667	0.01667	0 to 0.25	-0.233 to 0.01667

TABLE V
DIAMETER OF PIPES/VALVES FOR THREE-PIPE CONTROL SYSTEM FOR DIFFERENT NET HEAD OF WATER

hh (m)	Q (m^3/sec)	d (mm) at 100% q	D1 (mm) at 30% q	d2 (mm) at 10% q
10	13.33	1095.6	600.1	346.5
20	6.667	651.5	356.8	206
50	2.667	327.7	179.5	103.6
100	1.333	194.8	106.7	61.6
200	0.667	115.9	63.5	36.6

TABLE VI
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

APPENDIX B

The size of pipes/valves for 1000-kW power output of the hydro turbine for various heads of water is given in Table V, where $P_o = \eta q g h$

P_o	turbine output power in kW;
η	efficiency of turbine (0.75);
q	flow rate (m^3/s);
g	acceleration due to gravity (m^2/s) (taken as 10 here);
h	net head (m);
q	area of the pipe × velocity of water.
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 VI.

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 a 1000-kW dump load (water heater system) with controls is approximately Rs 10,00,000/- to Rs 15,00,000/-, while the cost for a 500-kW dump load (water heating system) with controls and on/off control valve is approximately Rs. 6,00,000 to Rs. 7,50,000.

TABLE VII
WATER AVAILABLE FOR IRRIGATION UNDER PREVAILING CONDITIONS AND ITS REVENUE PER YEAR FOR TWO PIPE SYSTEM

h (m)	Water for irrigation ($x10^6 m^3$)		Revenue (Indian rupees) x 10^5	
	Case – I	Case – II	Case – I	Case –II
10	151.14	115.60	77.07	57.80
20	77.09	57.82	38.54	28.91
50	30.84	23.13	15.42	11.56
100	15.41	11.56	7.71	5.78
200	7.71	5.78	3.86	2.89

The water saved by incorporating such a technique could be sold for irrigation purposes. The minimum amount of revenue generated by selling water for irrigation purposes is calculated for a two-pipe system considering two cases as follows:

Case—I: Load >500 kW for 8 hours in a day;

Case—II: Load >500 kW for 12 hours in a day.

It is assumed that water is required only for 55% time of the year by excluding rainy-season, harvesting period, etc. The cost of water supplied for irrigation by electric tube-wells is Rs 5 to Rs 15 per 100 m^3 of water, which depends upon the ground water level. The revenue generated per year by considering selling price as Rs 5 per 100 m^3 of water and transfer of water for irrigation under above conditions are given in Table VII.

The exact economic analysis is site specific, involving reduction in the cost of dump load, revenue generated by selling water for irrigation, cost of sluice gates/valves, and infrastructure. This infrastructure cost depends upon the water head, type of terrain, location of irrigation area from the plant, etc. The calculation of payback period requires elaborate data of the system, which is not in the scope of this paper.

It is very clear from the above prices that the cost of proposed system is much cheaper than the existing dump load based system. In addition to lesser price, the proposed system saves water for irrigation, which is of prime importance.

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