Reliability Evaluation of Micro Hydro-Photo-Voltaic Hybrid Power Generation Using Municipal Waste Water

R.K. Saket*, R.C. Bansal, and K.S. Anand Kumar

Abstract— *This paper describes a technology based on municipal waste water for electric power generation and evaluates the reliability of the micro-hydro-photo-voltaic (MHPV) hybrid power system using Gaussian distribution approach and flow duration curve (FDC). Reuse of municipal waste water of the city can be a stable, inflation proof, economical, reliable and renewable source of electricity. The hydro potential of waste water from community flowing through sewage system has been determined to produce a FDC by ordering the recorded water flows. Several factors such as design pressure, the roughness of the pipe's interior surface, method of joining, weight, ease of installation, accessibility to the sewage system, design life, maintenance, weather conditions, availability of material, related cost and likelihood of structural damage have been considered for a particular penstock. A MHPV has been proposed to provide reliable electric energy to Banaras Hindu University (BHU), Varanasi (India).*

Keywords— **Flow duration curve, micro-hydro-photo-voltaic hybrid power system, municipal waste water, reliability evaluation.**

1. INTRODUCTION

Small-hydro power (SHP) systems are relatively small power sources that are appropriate in many cases for individual users or groups of users who are independent of the electricity supply grid. Although this technology is not new, its wide application to small waterfalls and other potential sites is new. It is best suited to high falls with low volume, which occur in high valleys in the mountains. SHP is the application of hydroelectric power on a commercial scale serving a small community and are classified by power and size of waterfall. A generating capacity up to 10 MW is generally accepted as the upper limit of small hydro, although this may be stretched upto 30 MW in some countries. Small hydro can be further subdivided into mini hydro, usually defined as less than 1.0 MW, and micro-hydro which is less than 100 kW [1], [2]. Hydroelectric power is the technology of generating electric power from the movement of water through rivers, streams, and tides. Water is fed via a channel to a turbine where it strikes the turbine blades and causes the shaft to rotate to which generator is connected which converts the motion of the shaft into electrical energy. Small hydro is often developed using existing dams or through development of new dams whose primary purpose is river and lake water-level control, or irrigation. A small-scale hydroelectric facility requires a sizeable flow of water and a reasonable height of fall of water, called the head. Another advantage of using water resources is that hydraulic works can be made simple and large constructions, such as dams, are not usually required [1]-[5]. When dams are necessary, they affect less area than in lower zones because of the steepness of the terrain. Dams, which exploit the kinetic energy of water by raising small quantities of water to heights through the use of regulated pressure valves, can provide water for domestic uses and for agriculture in areas that are moderately higher than adjacent water courses.

Generally, in an autonomous hybrid power system, the wind/small-hydro power generators are the main constituents of the system and are designed to operate in parallel with local diesel grids. The main reasons are to obtain economic benefit of no fuel consumption by wind/hydro turbines, enhancement of power capacity to meet the increasing demand, to maintain the continuity of supply in the system, etc. Wind/small-hydro system is highly fluctuating in nature [6]-[8] and may affect the quality of supply considerably and even may damage the system in the absence of proper control mechanism. Main parameters to be controlled are the system frequency and voltage, which determine the stability and quality of the supply.

In a power system, frequency deviations are mainly due to real power mismatch between generation and demand, whereas voltage mismatch is the sole indicator of reactive power unbalance in the system [9], [10]. In a power system active power balance can be achieved by controlling the generation i.e. by controlling the fuel input to the diesel electric unit and this method is called automatic generation control (AGC) or load frequency control (LFC). Another method of controlling the frequency of hybrid system is by means of controlling the output power which includes dump load control, priority load control, battery energy storage (BES), flywheel storage, pump storage, hydraulic/pneumatic accumulators, superconducting magnetic energy storage

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(SMES), etc. [11]. Reactive power balance in the hybrid system can be obtained by making use of variable reactive power device e.g. static var compensator (SVC) [12]-[15].

Micro-hydro power system using waste water from community neither requires a large dam nor is land flooded. Only waste water from different parts of the city is collected to generate power which has minimum environmental impact. After proper treatment water can be provided to farmers for irrigation purpose. Micro-hydro power using waste water of sewage plant can offer a stable, inflation-proof, reliable, economical and renewable source of electricity. This technology has been designed and implemented at Institute of Technology, BHU, Varanasi (India). This paper presents a new renewable resource of hydroelectric power generation using waste water from community of the city.

2. SELECTION OF BASIC COMPONENTS OF SYSTEM

The principal components of the micro-hydro power system using sewage system are shown in Fig. 1. Interconnection of the micro hydro and PV system for reliable operation of the hybrid plant is shown in Fig. 2. A tailrace and solar pump through which the water is released back of the sewage storage plant to maintain head of the water according to flow rate v/s duration curves is shown in Fig. 3. The basic components of typical hybrid micro-hydro power plant using waste water from community are as follows:

- An intake or weir to divert stream flow from different parts of the city.
- A sewage line to carry water flow to the forebay from the intake of the system.
- A forebay tank and trash rack to filter debris and prevent it from being drawn into the turbine at the penstock pipe intake.
- A penstock pipe to convey the waste water to the power source.
- Civil work components viz. head work, intake, headrace canal/sewage lines, forebay/sewage reservoir tank, penstock pipe, power house and tailrace with back up system.
- Power house components (turbines, generators, drive system and controllers). A water turbine converts the hydro energy into mechanical energy that drives a generator (induction, synchronous or permanent magnet AC generator. which generates electrical power and an automatic control mechanism provides stable electrical power using municipal waste water of the city.
- Transmission and distribution network from generating plant to load centre.

(a) Selection of penstock pipe

The penstock is often the most expensive item in the project which may cost upto 40% of total project cost. Several factors should be considered when deciding which material to use for a particular penstock design pressure i.e. the roughness of the pipe's interior surface, method of joining, weight, ease of installation, accessibility to the site, design life, maintenance, weather conditions, availability, relative cost and likelihood of structural damage [3]. The pressure rating of the penstock is critical because the pipe wall must be thick enough to withstand the maximum water pressure otherwise there may be a risk of bursting. The pressure of the water in the penstock depends on the head, the higher the head, the higher the pressure. The most commonly used materials for a penstock are mild steel, high density poly ethylene (HDPE) and unplastified polyvinyl chloride (uPVC). The uPVC exhibits excellent performance over mild steel and HPDE in terms of least friction losses, weight, corrosion, and cost, etc.

(b) Selection of turbines

Turbine is connected either directly to the generator or via gears or belts and pulleys, depending on the speed required for the generator. The choice of turbine depends mainly on the head and the design flow for the proposed micro-hydro power installation. The selection also depends on the desired running speed of the generator. To adjust for variations in stream flow, water flow to these turbines can be controlled by changing nozzle sizes or by using adjustable nozzles. Turbines used in the hydro system can be classified as Impulse (Pelton, Turgo and Cross flow), Reaction (Frencis, Propeller, and Kaplan) and Waterwheels (undershort, breastshot and overshot). Typical efficiency of Impulse and Reaction turbines range 80-95% and for Waterwheels it ranges 25-75% [3].

(c) Selection of generator

Induction and synchronous generators are used in power plants and both are available in three phase or single phase systems. Induction generators are generally appropriate for micro hydro power generation [1]. Induction generator offers many advantages over a conventional synchronous generator as a source of isolated power supply. Reduced unit cost, ruggedness, brush less (in squirrel cage construction), reduced size, absence of separate DC source and ease of maintenance, self-protection against severe overloads and short circuits, are the main advantages [16]-[21]. Capacitors are used for excitation and are popular for smaller systems that generate less than 10 to 15 kW. All generators must be driven at a constant speed to generate steady power at the frequency of 50 Hz. The two pole generator with a speed of 3000 RPM is too high for practical use with micro hydro power system. The 1500 RPM, four pole genitor commonly used. Generator operating at less than 1000 RPM becomes costly and bulky and to match the speed of the generator to low speed of the turbine, a speed increasing mechanism such as belt and /or gear box is required.

Fig. 1. Principal components of micro-hydro power systems

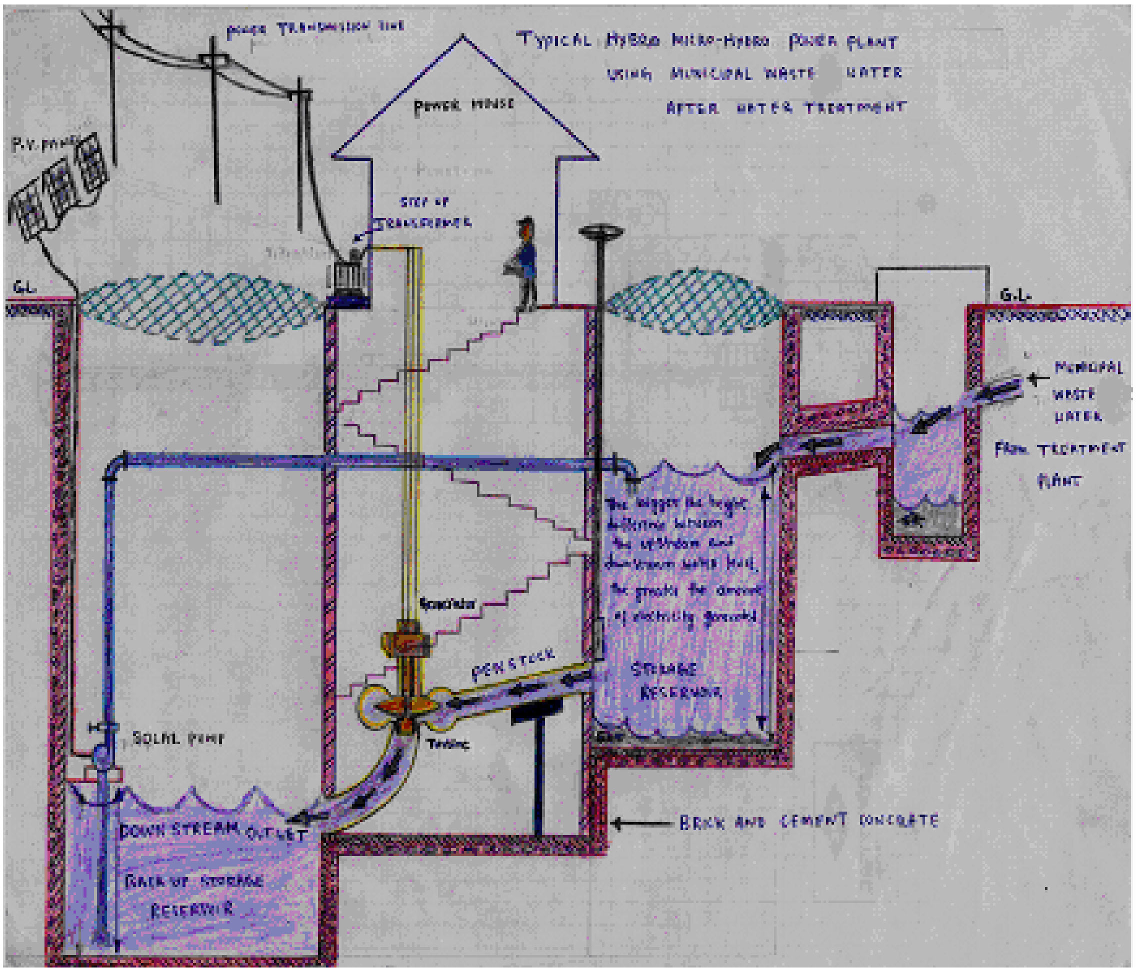

Fig. 2. Interconnection of the Micro Hydro and PV system for reliable operation of the hybrid power system

Fig. 3. Solar pump for recycle waste water from the down stream to upstream storage reservoir

3. MEASUREMENT OF POTENTIAL POWER WITH VARIOUS HEAD AND WATER FLOW RATES

The theoretical amount of power available from a micro-hydro power system is directly related to the flow rate (Q), head (H) and the force of gravity (g) as given below,

$$P_{th} = Q \times H \times g \quad (1)$$

To calculate the actual power output (P_{act}) from micro-hydro power plant, it is required to consider friction losses in the penstock pipes and the efficiency of the turbine and generator. Typically overall efficiencies for electrical generating systems can vary from 50 to 70 % with higher overall efficiencies occurring in high head systems. Therefore, to determine a realistic power output as shown in Table 1, the theoretical power must be multiplied by an efficiency factor of 0.5 to 0.7 depending on the capacity and type of system as given below.

Table 1. Typical power output with various head and water flow rates

Head (m)	Flow rates (lps)					
	10	20	40	60	80	100
	Power output (W)					
1	49	98	196	294	392	490
2	98	196	392	588	784	980
4	196	392	784	1176	1568	1960
8	392	784	1568	2352	3136	3920
10	490	980	1960	2940	3920	4900
15	735	1470	2940	4410	5880	7350
20	980	1960	3920	5880	7840	9800
30	1470	2940	5880	8820	14112	17640
40	1960	3920	7840	14112	18816	23520
60	2940	5880	14112	21168	28224	35280
80	3920	7840	18810	28224	37632	47040
90	4410	8820	21168	31752	42336	52920
100	4900	9800	23520	35280	47040	58800

$$P_{act} = Q \times H \times g \times e \quad (2)$$

where e = efficiency factor (0.5 to 0.7).

4. FLOW DURATION CURVE AND ENERGY CALCULATION

In the paper annual as well as monthly/daily flow duration curve (FDC) has been obtained for municipal waste water from community of the city by recording water flows as shown in Fig. 4 (a). The load duration curve (LDC) of the hybrid system has also been obtained according to reliability evaluation of the plant as shown in Fig. 4 (b). The FDC and LDC are used to asses the expected availability of water flow, load variations and power capability to select the type of the turbine and generator. From Fig. 4 (a) it is seen that, there is a difference in waste water flow between summer and winter and this can affect the power output produced by a micro hydro power system.

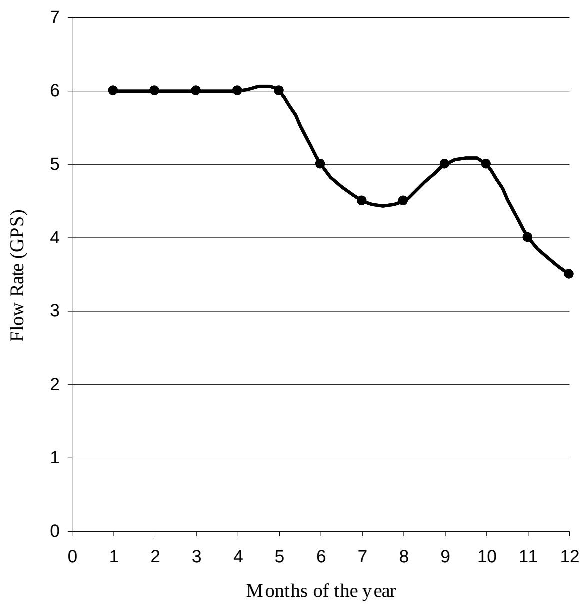

Fig. 4(a) Typical Annual Duration Cureve of System

These variations have been considered in the estimation of total energy generation expected from the site with recycle of the water using solar pumping system as shown in Fig. 3. Peak demand as shown in Table 2 has been calculated to evaluate the reliability [22]-[26] of the hybrid power system.

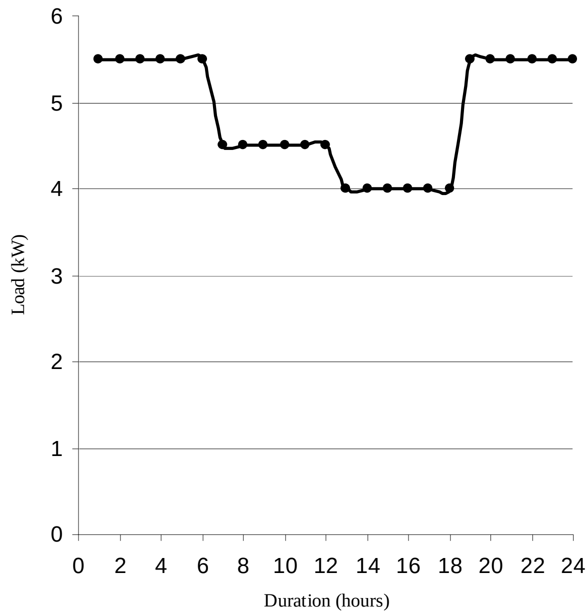

Fig. 4(b). Typical Load Duration Curve of the System

Table 2. Sample load analysis

Appliances	Power rating (W)	Hours /day	Monthly consumption (kWh)	Annual consumption (kWh)
Fluorescent Lamps (4 No.)	160	8	38.4	460.8
Colour Television (1 No.)	140	3	12.6	151.2
Refrigera--tor (1 No.)	500	8	120	1440
Water pump (1 No.)	800	1.5	36	432
Computer (1 No.)	200	10	60	720
Total energy consumption			267	3204

5. RELIABILITY EVALUATION OF SYSTEM

The load on the MHPV hybrid generating station according to load duration curve of the sewage system to have a Gaussian distribution for a specified time interval is given as follows.

$$f\left(P_d\right)=\frac{1}{\sigma_d\sqrt{2\pi}}e^{-0.5\left(\frac{P_d-\bar{P}_d}{\sigma_d}\right)^2} \qquad (3)$$

The aggregate generation capacity model is approximated as Gaussian [22]-[23].

$$f(C)=\frac{1}{\sigma_c\sqrt{2\pi}}e^{-0.5\left[\frac{C-\bar{C}}{\sigma_c}\right]^2} \qquad (4)$$

P_s is known as probability of success and can be expressed as follows

$$P_s=\int_{-\infty}^{\infty}\int_{-\infty}^{C}\frac{1}{2\pi\sigma_c\sigma_d}e^{-0.5\left[\frac{C-\bar{C}}{\sigma_c}\right]^2}e^{-0.5\left(\frac{P_d-\bar{P}_d}{\sigma_d}\right)^2}dc\,dP_d \qquad (5)$$

Equation (5) can be written as follows [24].

$$P_s=\int_{-\infty}^{\infty}\left[\int_{-\infty}^{z}e^{-0.5\left(x^2+y^2\right)}dy\right]dx \qquad (6)$$

where β is given as follows.

$$\beta=\frac{\bar{C}-\bar{P}_d}{\sqrt{\sigma_d^2+\sigma_C^2}}$$

Equation (6) is simplified as follows.

$$P_s=\int_{-\infty}^{\beta}\left[\int_{-\infty}^{\infty}\frac{1}{\sqrt{2\pi}}e^{-0.5\left(x'^2\right)}dx'\right]e^{-0.5\left(y'^2\right)}dy'$$

$$=\int_{-\infty}^{+\beta}\frac{1}{\sqrt{2\pi}}e^{-0.5\left(y'^2\right)}dy'=\varphi(\beta) \qquad (7)$$

Where, φ [β] is the area under the normal distribution curve having 0 mean and standard deviation [N (0, 1)] 1 from - ∞ to β and this value can be conveniently obtained from standard normal distribution table.

6. RESULTS AND DISCUSSIONS

A MHPV hybrid power system can be reliable and provide stable electric power. The reliability of MHPV hybrid power system has been evaluated at different conditions of the LDC and FDC using a methodology based on Gaussian distribution approach. The mean load has been assumed 1.0 kVA. The mean capacity and standard deviation data are given in Table 3.

The standard deviations for both generating capacity and mean load have been assumed 10% of the generating capacity and mean load respectively. Using the relation (7), the failure probability has been evaluated assuming generating capacity $\bar{C}$ = 1.2 kVA as P_F = 0.1013.

Now the generating capacity is increased in step of 50 VA at the fixed value of the mean load at 1.0 kVA and the probability of failure has been calculated. Various plots of failure probability v/s generating capacity are shown in Fig. 5, selecting the following values of the standard deviations.

Table 3. Mean capacity and standard deviation

$\bar{C}$	1.2 kVA	1.25 kVA	1.3 kVA	1.35 kVA	1.4 kVA
σ_C = 10%	120	125	130	135	140
σ_C = 20%	240	250	260	270	280
σ_C =15%	180	187	195	202	210

(a) [σ_1 =10% of $\bar{L}$ and σ_C =10% of $\bar{C}$] = σ_1

(b) [σ_1 =10% of $\bar{L}$ and σ_C =20% of $\bar{C}$] = σ_2

(c) [σ_1 =20% of $\bar{L}$ and σ_C =10% of $\bar{C}$] = σ_3

(d) [σ_1 =20% of $\bar{L}$ and σ_C =20% of $\bar{C}$] = σ_4

The various curves are drawn for various combinations of σ_C and σ_1 as shown in the Fig. 5. It is observed from curve A and B that for the same generating capacity of the system, the probability of failure with σ_2 is more than σ_1. This is due to fact that large uncertainty involved in generating capacity distribution function.

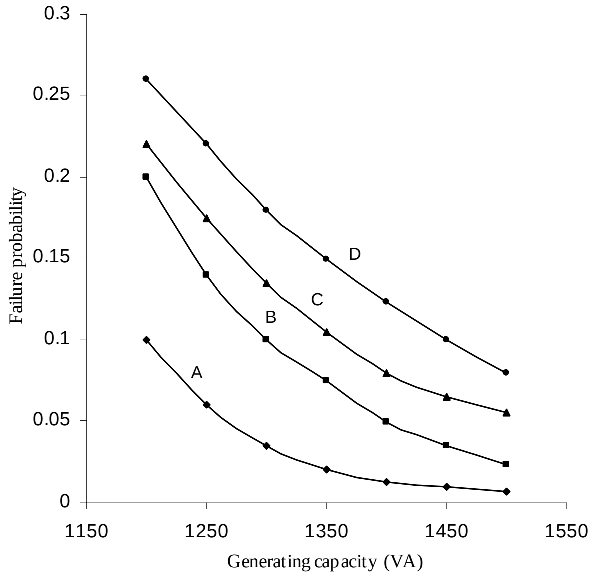

Fig. 5. Failure probability v/s generating capacity of power system

Similarly by observing the curve A and C for the same generating capacity the probability of failure for σ_2 is more than σ_3 and so on. From the curve D, the failure probability for any generating capacity is more than from other curves. In summary, the probability of failure increases with either increase of σ_1 or increase of σ_c or both σ_1 and σ_c.

7. CONCLUSIONS

A MHPV hybrid power system is stable, cheap and capable of producing reliable power because the head/pressure of the sewage reservoir has been maintained at constant using back up service by PV pump in summer and winter cycles of the country. A new methodology has been introduced in this paper for hybrid generating system reliability evaluation using different load and generation models. The evaluation of loss of load probability has been based on load generation models as peak load of the MHPV hybrid power plant is less than generating capacity, failure probability is negligible; and normal distribution is assumed as generation capacity model and load duration curve as load models and normal distribution model as generating capacity. Further in all cases it is confirmed that the failure probability of the system increases with an increase in variance of load or generation capacity.

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NOMENCLATURE

P_d = Demand at the generating stations

$\bar{P}_d$ = Average or mean load of plant

σ_d = Standard deviation of demand

C = Capacity of the generating station

$\bar{C}$ = Mean capacity of the plant

σ_c = Standard deviation of capacity

P_F = Probability of failure of generating station

P_S = Probability of success of generating station

P_{th}= Theoretical power output in kW

Q = Usable flow rate in m^3/s

H = Gross head in m

g = Gravitational constant ($9.81 m/s^2$)

LOLP = Loss of load probability

f (L) = Normal distribution

L = Total load in VA

Φ = Rotational angle

Φ(β) = Area under normal distribution curve

S = Safety factor

n = Total duration of the study

P_{fi} = Failure probability for L_i th load level

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