Investigations on Riverline Hydrokinetic Energy as Distributed Generation

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Abstract

The kinetic energy in flowing water can be converted and fed directly to the electrical distribution line running along river or canal. The larger distance between distribution lines and substation not only causes reduction in voltage at nodes up to tail end of the feeder but also increases the active and reactive power losses in the branches of feeder. By connecting the electrical energy generated from flowing water to nodes in optimal way results in saving of active and reactive power losses and also improves voltage profile. In this paper, methodology for determination of technically recoverable hydrokinetic potential is discussed utilizing different software tools and mathematical calculations. The improvement in voltage profile and reduction in active and reactive power losses are determined using proposed methodology for optimal sizing of hydrokinetic turbines using genetic algorithm.

I Introduction

Hydropower being one of the most ancient, cost effective and not intermittent renewable form of energy, generates approximately one fifth of world's electricity. Conventional hydropower plants utilize hydrostatic energy by impoundment of water behind dams for creating a hydraulic head for generating electricity [1]. In hydrokinetic energy conversion kinetic energy of flowing water is used for generation of electricity [2]. Hydrokinetic energy conversion requires lesser construction, not site specific and has low gestation period in comparison with conventional hydropower electricity generation. Distributed generation is an electric power source installed directly to the distribution network or on the customer site of meter [3]. The distributed generation in the form of non renewable and renewable energy source like wind and solar have been analyzed under various studies [3,4,5] but the implementation of hydrokinetic energy source from the view point of voltage profile improvement and reduction in active and reactive power loss need to be analyzed. The hydrokinetic energy utilized as distributed generation in conjunction with any of other energy sources may it be renewable or non renewable is analyzed in present case for voltage profile, active and reactive power loss and the technical recoverable power in the study for radial distributed 33 Bus systems.

II Methodology

The river or canal segments along the distribution networks on Google Earth is chosen and for identified canal segment the data like, monthly/weekly discharge, digital evaluation model, recognized river segments with stable bed slope and channel roughness (Manning's coefficient) is collected. The river line hydrokinetic power (P_{th} in watts) theoretically available in a given river /canal segment can be defined as

$$P_{th} = \gamma Q \Delta H \quad (1)$$

Here γ is specific weight of water ($9.81X\ 10^3 Nm^3$), Q is discharge (m^3/s); and ΔH is level difference in entry and end of water surface level in river segment (m).

The river line hydrokinetic power (P_{tech} in watts) for selected river selected river segment is the recoverable fraction of the theoretically calculated power under the following technical constraints and assumptions [4, 6]

(i) Water depth at the 90 percentage flow from flow duration curve should be greater than 2 m
(ii) Average velocity at the 90 percentage flow should be greater than 0.5 m/s
(iii) Device spacing in hydrokinetic farming adopted from rule of thumb i.e. spacing between turbines across the cross section of river will be '2D' and spacing between turbines along the river will be '10D' where 'D' is diameter of hydrokinetic turbine.
(iv) Water to wire efficiency is around 30% considering device, gearbox, power conditioning device, step up transformer etc.
(v) Wake up effect and back effects due to turbines present in water

River Analysis System (HEC-RAS) software from Hydrologic Engineering Center's (CIEWR-HEC) provides tools for user to simulate one-dimensional steady flow, one and two-dimensional unsteady flow for river or channel [5, 7]. Input channel geometry, Manning's coefficient (separately for left bank, right bank and main channel), slope and using the flow condition according to 90 percentage flow from flow duration curve. From simulation results the depth of water and average velocity are recorded. In case the water depth is below 2 m or average water velocity is less than 0.5 m/s than deployment of hydrokinetic farming in given segment is not technically feasible.

Let 'D_{90}' be the water depth at 90 percentage flow when no hydrokinetic devices are present. Diameter of turbine (D) can be selected of size 80 percentage of 'D_{90}'. The presence of the hydrokinetic turbines would result wake up effects and back effects resulting in decrease of water velocity and increase in water depth. This dragging effect in presence of these devices can be incorporated in to effective Manning's coefficient 'n_e' from natural channel bottom Manning's coefficient 'n' [6, 8].

$$n_e = n\,(b^{1/3} - 0.28263.b^{-1/3} - 0.139296)^{5/3} \quad (2)$$

Where $b = 0.46088a + ((0.46088.a + 0.68368)^2 + 0.022578))^{1/2} + 0.68368$ (3)

Here $a = \left(\frac{3}{4}\frac{\tau(1+\epsilon)NA_r}{n^2 g.wL}\right).\sqrt[3]{h}$ (4)

Where 'τ' is turbine efficiency, 'ϵ' blockage ratio (fraction of river cross-section occupied by devices), 'N' is total number of devices in river segment, 'A_r' is the frontal (or swept) area of the device (m^2), 'h' is water depth (m), and 'w' is the width of the river or channel that is occupied by device (m).

Manning's coefficient is modified from 'n' to 'n_e' in HEC-RAS, and through simulation average velocity (V_{90}) and water depth which would result after placement of hydrokinetic devices are obtained. Total technical hydrokinetic potential ($P_{tech-90}$) in watts that can be recovered from the channel segment under consideration at 90 percentage flow will be

$P_{tech-90} = \tau\frac{\rho}{2}(V_{90})^3 N.A_r$ (5)

Water depth 'h' is obtained without placement of hydrokinetic devices through simulation in HEC-RAS for different flow conditions 75, 50, 25, 5 (percentage of time). Using this obtained water depth modified Manning's coefficient is calculated using equ. (2). Average velocities of water after placement of hydrokinetic turbines with new values of Manning's coefficient are obtained by simulating again. Consider 'd' as the proportion of total depth then velocity of water can be determined using following relation

$V = 0.8395d^2 + 0.315d + 1.1338$ (6)

The net velocity experienced by hydrokinetic turbine will be the velocity difference at height of '0.2x D_{90}' from bottom of the channel to the velocity at height 'D_{90}' from the bottom. These bottom and top water velocities experienced by hydrokinetic turbine can be found from the curve shown in Fig. (1).

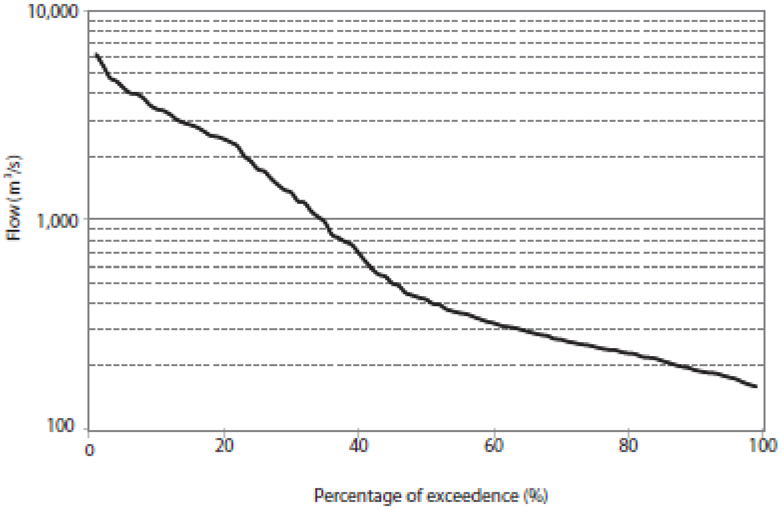

Fig. (1): Flow duration curve of Ganga River at Kaudilya

The technical recoverable hydrokinetic power potential of channel under consideration using equ. (6) is calculated for different flow condition (75, 50, 25, 5 percentage of time). The data related to the distribution system is collected and further analyzed by performing load flow analysis using Backward & Forward sweep method. The flow chart of proposed methodology is depicted in Fig. (2).

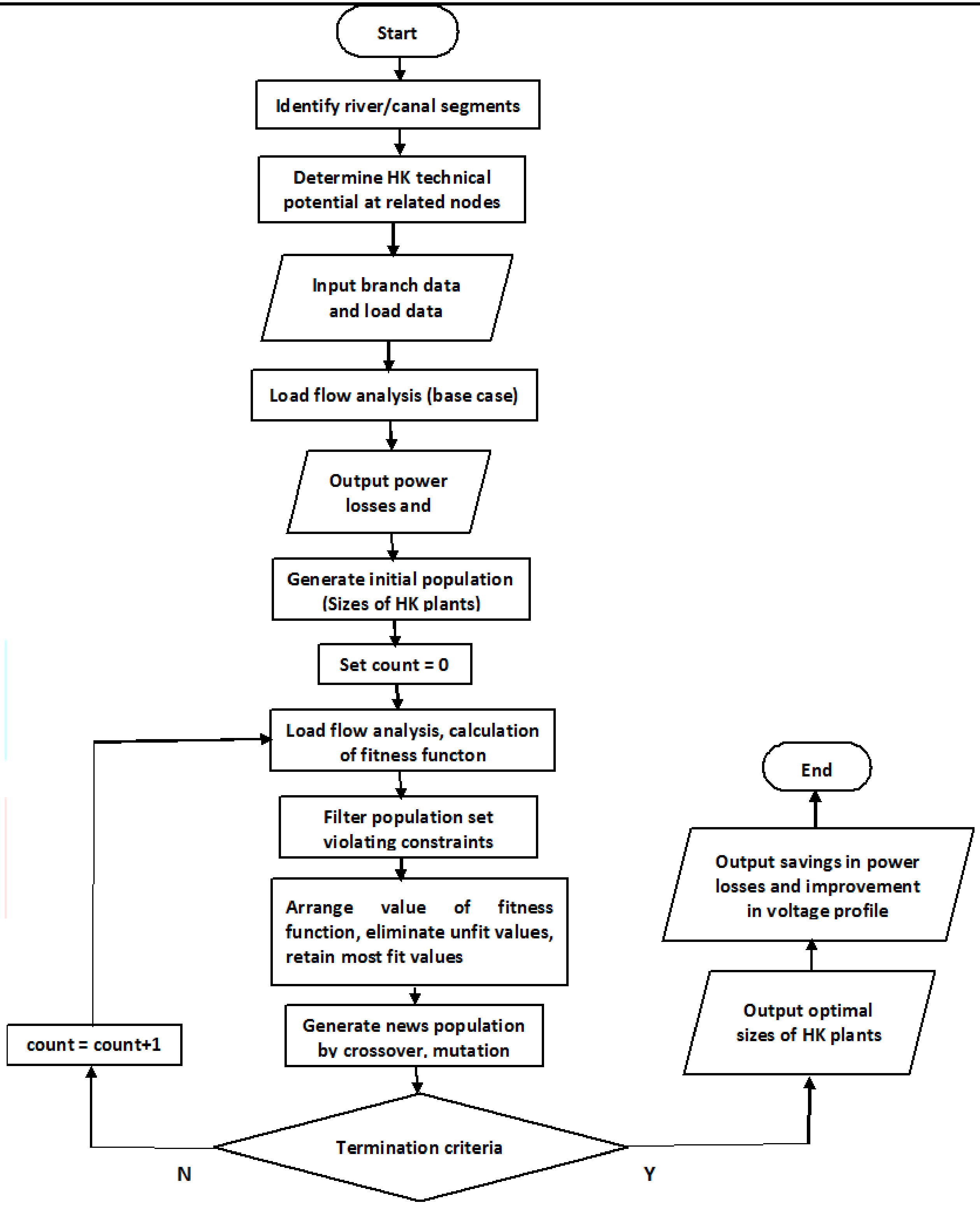

Fig. (2): Flow chart of proposed methodology

Let $HKEP_1$, $HKEP_2$, ……..$HKEP_m$ are the hydrokinetic power potential estimated in river or channel segments at corresponding identified nodes of distribution network, where ‘m’ is the total number of nodes related to hydrokinetic power plant, then optimal active power generation capacity HKP_1, HEP_2, ……..HEP_m of hydrokinetic plants is to be determined as perspective of distributed generation. Optimization is performed by Genetic Algorithm with following objective function and constraints function.

a) Active and reactive power minimization

$$P_L = \sum_{i=1}^{N-1} \mathrm{I_L^2 R_i} \text{ and } Q_L = \sum_{i=1}^{N-1} \mathrm{I_L^2 RX_i} \tag{7}$$

Here I, R, X are branch current, resistance and reactance respectively.

b) Minimization of size of hydrokinetic plants

$$S = \sum_{j=1}^{m} \mathrm{HKP_j} \tag{8}$$

Here ‘S’ is the total capacity of hydrokinetic plants.

The multi-objective function F can be written as

$$\min F = \mathrm{w_1 P_L} + \mathrm{w_2 Q_L} + \mathrm{w_3} S \tag{9}$$

Here w_1, w_2 and w_3 are weight age constants.
Following constraints should be considered for discussed multi objective functions

c) **Voltage profile limit:** The node voltage functions 'V_i' is restricted by its upper limit 'V_i^{max}' and lower limit 'V_i^{min}' for all the buses.

$$V_i^{min} \leq V_i \leq V_i^{max} \qquad (10)$$

d) **HKP active power generation limit**: Active power generation 'HKP_j' from the hydrokinetic plant connected to node should be less than or equal to the estimated power potential '$HKEP_j$' at that particular node.

$$0 \leq HKP_j \leq HKEP_j, \qquad \text{where } j=1 \text{ to } m \qquad (11)$$

e) **Reversal power flow:** There should be no reversal power flow from hydrokinetic plant to substation.

$$\sum_{j=1}^{m} HKP_j \leq \text{total load} + \text{total active power loss} \qquad (12)$$

Other constraints like thermal limit of feeder, phase angle limit and short circuit level limits can be incorporated as per the case.

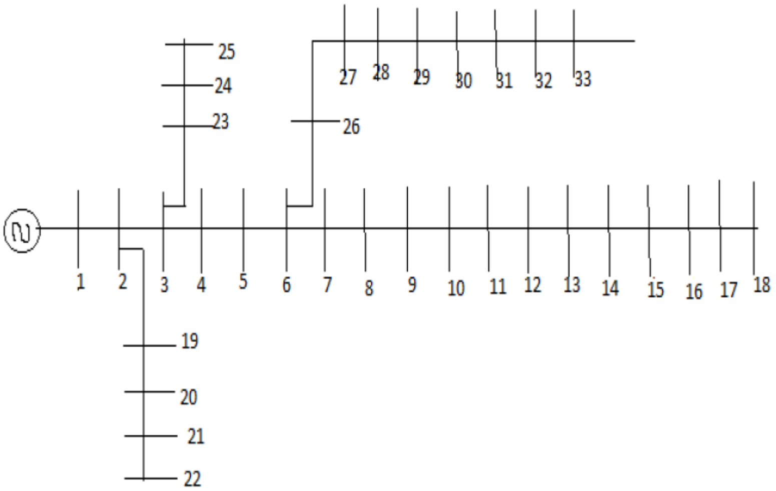

Fig. (3): IEEE 33 Radial distribution system

Let us consider the radial 33 bus distribution shown in Fig. (3) for analysis, where feeder from node 3 to 18 is assumed to run along the road corresponding to river and nodes 3, 7, 8, 9, 11, 16, 17 are assumed to be close to the river and hence, are selected for generation from hydrokinetic energy. The line data and peak loads related to distribution system under study are listed in the Table (1).

Table 1: Line data and Load data of IEEE 33 bus Radial Distribution System

Branch Number	Sending end bus	Receiving end bus	Resistance R (Ω)	Reactance X (Ω)	Bus Number	Active Power P_L (KW)	Reactive Power Q_L (KVAR)
1	1	2	0.0922	0.047	1	0	0
2	2	3	0.493	0.2511	2	100	60
3	3	4	0.366	0.1864	3	90	40
4	4	5	0.3811	0.1941	4	120	80
5	5	6	0.819	0.707	5	60	30
6	6	7	0.1872	0.6188	6	60	20
7	7	8	0.7114	0.2351	7	200	100
8	8	9	1.03	0.74	8	200	100
9	9	10	1.044	0.74	9	60	20
10	10	11	0.1966	0.065	10	60	20
11	11	12	0.3744	0.1238	11	45	30
12	12	13	1.468	1.155	12	60	35
13	13	14	0.5416	0.7129	13	60	35
14	14	15	0.591	0.526	14	120	80
15	15	16	0.7463	0.545	15	60	10
16	16	17	1.289	1.721	16	60	20
17	17	18	0.732	0.574	17	60	20

18	2	19	0.164	0.1565	18	90	40
19	19	20	1.5042	1.3554	19	90	40
20	20	21	0.4095	0.4784	20	90	40
21	21	22	0.7089	0.9373	21	90	40
22	3	23	0.4512	0.3083	22	90	40
23	23	24	0.898	0.7091	23	90	50
24	24	25	0.896	0.7011	24	420	200
25	6	26	0.203	0.1034	25	420	200
26	26	27	0.2842	0.1447	26	60	25
27	27	28	1.059	0.9337	27	60	25
28	28	29	0.8042	0.7006	28	60	20
29	29	30	0.5075	0.2585	29	120	70
30	30	31	0.9744	0.963	30	200	600
31	31	32	0.3105	0.3619	31	150	70
32	32	33	0.341	0.5302	32	210	100
					33	60	40

The genetic algorithms (GA) optimization technique shown in Fig. (4) is implemented for the search of the optimal solution. The GA is optimization methods that implement a search process inspired from the process of biological selection and biological genetics. Genetic Algorithm (GA), a part of the group of Evolutionary Algorithms, is direct, parallel, stochastic method for global search and optimization tool that imitates the evolution of the living beings, described by Charles Darwin. Three main principles of the natural evolution [94; 7].namely; (a) reproduction, (b) natural selection, and (c) diversity of the species, are maintained by the differences of each generation with the previous one.

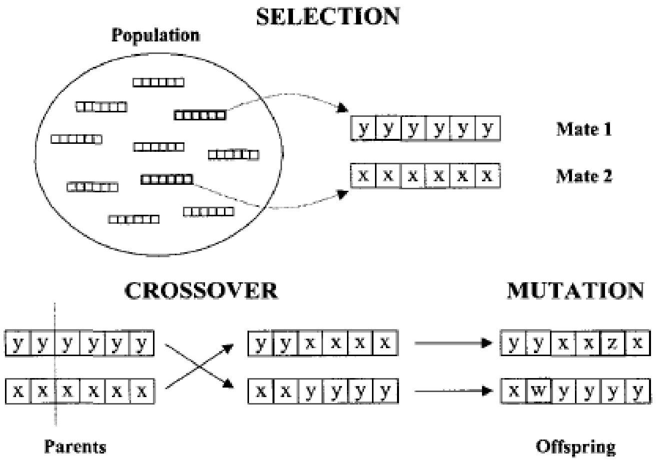

Fig. (4): GA Operator [95; 8]

As the GA needs scalar fitness function to work, it is required to propose a combination of all the objectives into a single objective by using a weighted sum of the single objective functions. This methodology can be applied to determine non dominated solution to be used as an initial solution [67; 9].

The flow chart for Genetic Algorithm is depicted in Fig. (5) and the steps are [96; 10]:

1. Generate initial population – the first generation is randomly generated, by selecting the genes of the chromosomes among the allowed alphabet for the gene. Because of the easier computational procedure, it is accepted that all populations have the same number (N) of individuals
2. Calculation of the fitness values of the function that we want to minimize or maximize.
3. Check for termination of the algorithm – it is possible to stop the genetic optimization by:
   - Value of the function – the value of the function of the best individual is within defined range around a set value. It is not recommended to use this criterion alone, because of the stochastic element in the search procedure, the optimization might not finish within sensible time;
   - Maximal number of iterations – this is the most widely used stopping criteria. It guarantees that the algorithms will give some results within some time, whenever it has reached the extremities or not;

- Stall generation – if within initially set number of iterations (generations) there is no improvement of the value of the fitness function of the best individual the algorithms stops.

4. Selection – between all individuals in the current population are chose those, who will continue and by means of crossover and mutation will produce offspring population. At this stage elitism could be used – the best n individuals are directly transferred to the next generation. The elitism guarantees, that the value of the optimization function cannot get worst (once the extremity is reached it would be kept).
5. Crossover – the individuals chosen by selection recombine with each other and new individuals will be created. The aim is to get offspring individuals that inherit the best possible combination of the characteristics (genes) of their parents.
6. Mutation – by means of random change of some of the genes, it is guaranteed that even if none of the individuals contain the necessary gene value for the extremity, it is still possible to reach the extremity.

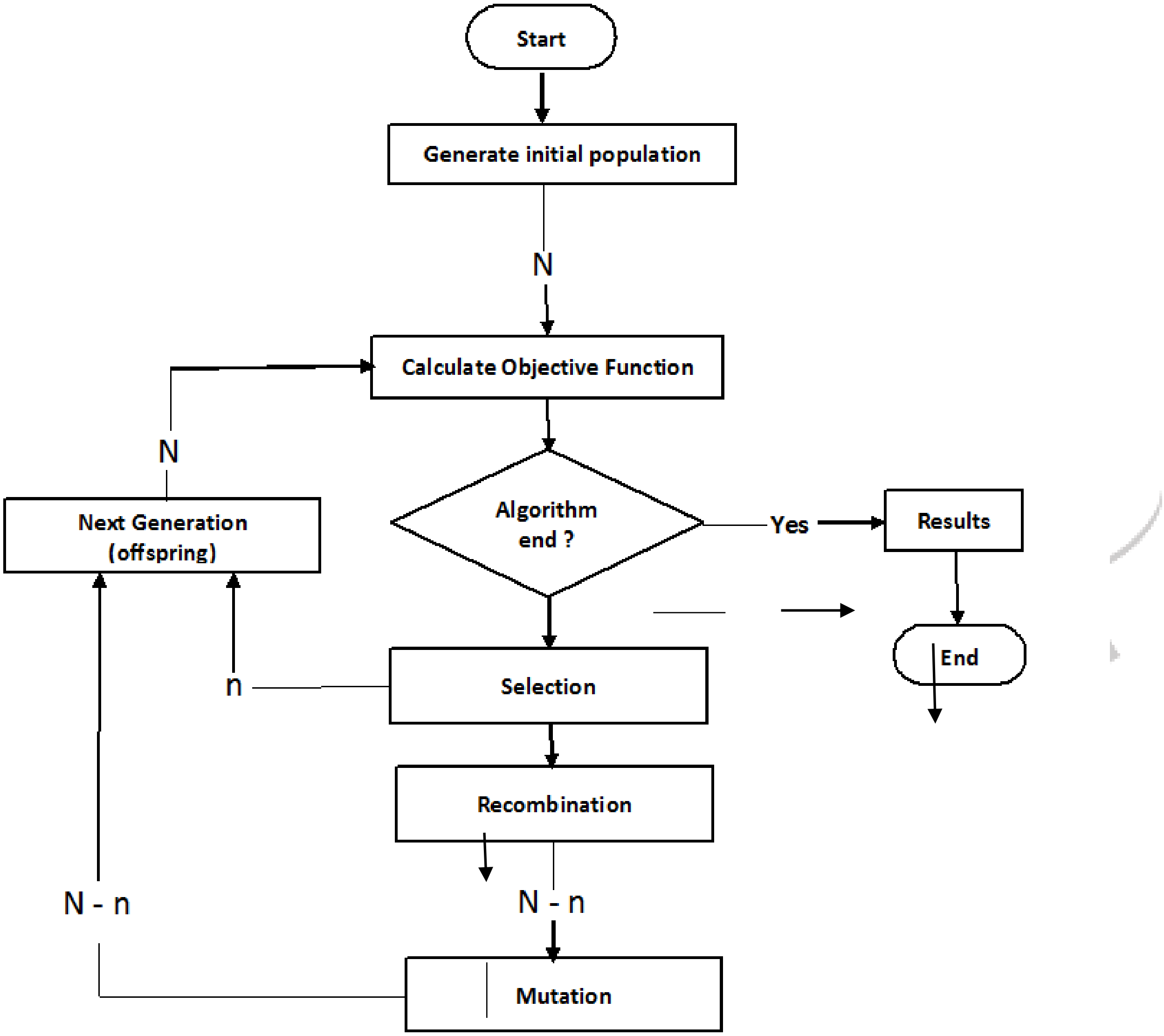

Fig. (2): Flowchart for Genetic Algorithm

New generation – the elite individuals chosen from the selection are combined with those who passed the crossover and mutation, and form the next generation.

III Results and Discussions

Estimated technically recoverable hydrokinetic potential is calculated for river segments at 90% and 5% dependability and is listed in Table (2).

Table 2: Estimated technical HK Potential for river segments

Sr. No.	Location	Bus No.	Estimated technically recoverable hydrokinetic potential (KW)		No. of HK turbines
			At 90 % dependability	At 5% dependability	
1	River segment 1	3	72	1032	33
2	River segment 2	7	412	8369	154
3	River segment 3	8	466	1996	70
4	River segment 4	9	105	847	26
5	River segment 5	11	36	314	8
6	River segment 6	16	482	1541	30
7	River segment 7	17	832	2601	45

In the case study, the turbine radius is 0.8 m, spacing between turbines in row is 3.2 m and the spacing between rows is 16 m for hydrokinetic farming. Optimization for capacity hydrokinetic plants at different nodes is performed using Genetic Algorithm solver in MATLAB 2016a environment. HKP1 to HKP7 are assumed to be variables for optimal capacity for HK plants.

Objective function (*f*) = w_1 X total real power loss + w_2 X total reactive power loss+w_3 X total capacity of Hydrokinetic plant + Penalty function for node voltage (13)

Total capacity of HK plant =HKP1 + HKP2 + …………+HKP7

Penalty function =0 for -10% of nominal $\leq$ voltage $\leq$ +10% of nominal voltage
= 1000X voltage difference , otherwise

Weightage factors: $w_1 = 0.7$
$w_2 = 0.2$
$w_3 = 0.1$

Weightage factor for real power loss is kept more as it is merely related to energy loss in distribution system.

Constraints:

Node voltage should be in limit. This is incorporated in objective function in the form of penalty function.

Total capacity of HKL plant (HKP1+HKP2+ ………HKP7) $\leq$ total peal load (3715 KW)

As variable for capacity of HK plant should be less than or equal to estimated potential for that node, lower and upper bounds is set in following way

$0 \leq$ HKP 1 $\leq$ 1032 KW
$0 \leq$ HKP 2 $\leq$ 3715 KW
$0 \leq$ HKP 3 $\leq$ 1996 KW
$0 \leq$ HKP 4 $\leq$ 847 KW
$0 \leq$ HKP 5 $\leq$ 314 KW
$0 \leq$ HKP 6 $\leq$ 1541 KW
$0 \leq$ HKP1 $\leq$ 2601 KW

Optimization is done using listed variables with objective and constraints function discussed. The plots for mean fitness value with generation and best fitness value with generation are shown in Fig. (6) & (7) respectively. Optimization has been done after 5 generation where the mean fitness value is 0.458815 and the best fitness value is 0.458813. The plots for minimum, maximum, and mean score values in each generation is enumerated in Fig. (8).The best individual in the last generation is depicted in Fig. (9).

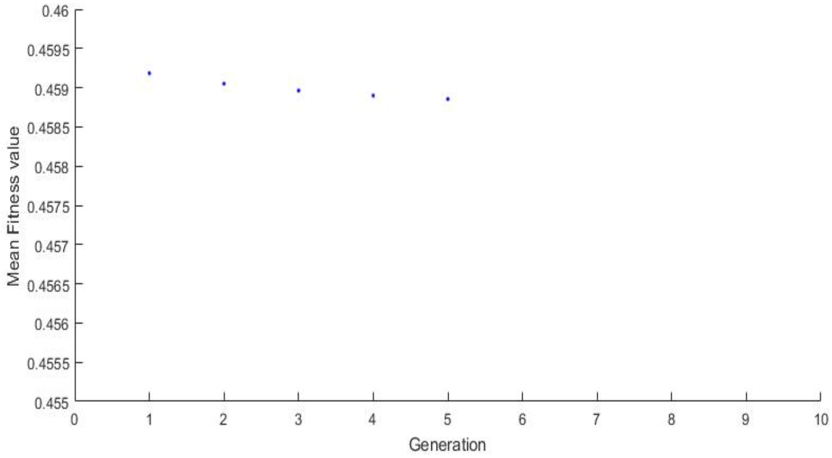

Fig.(6): Plot for Mean Fitness Value

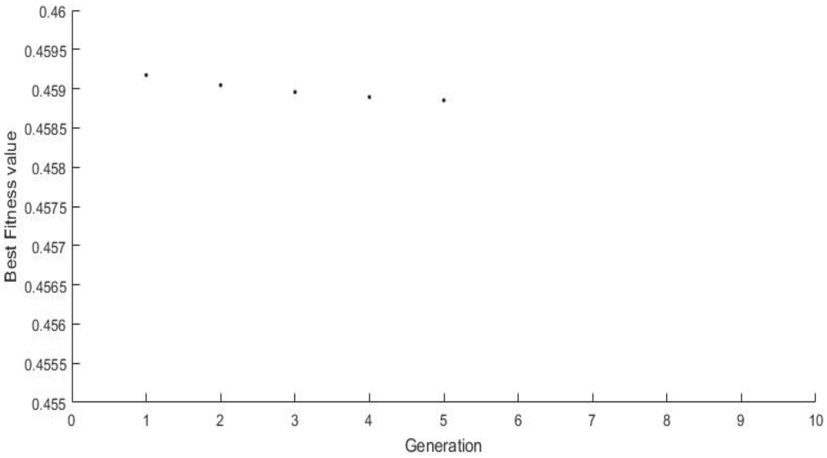

Fig. (7): Plot for Best Fitness Value

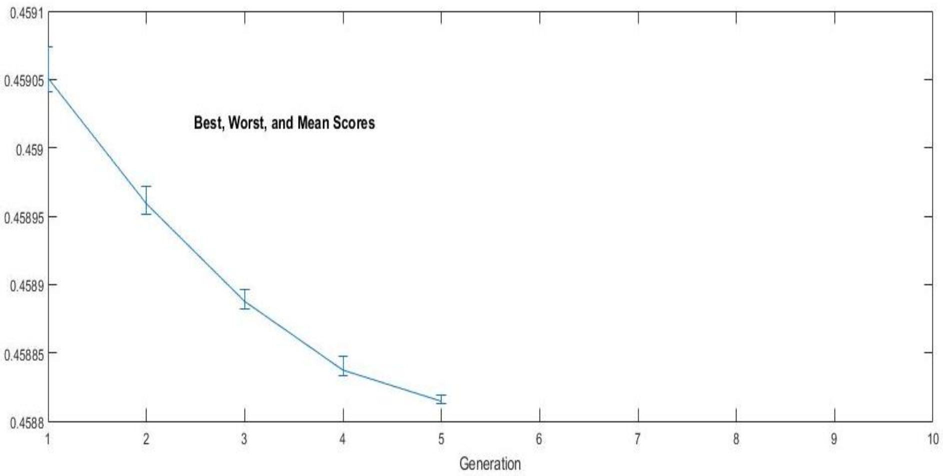

Fig. (8): Best, Worst and Mean Scores with Generation

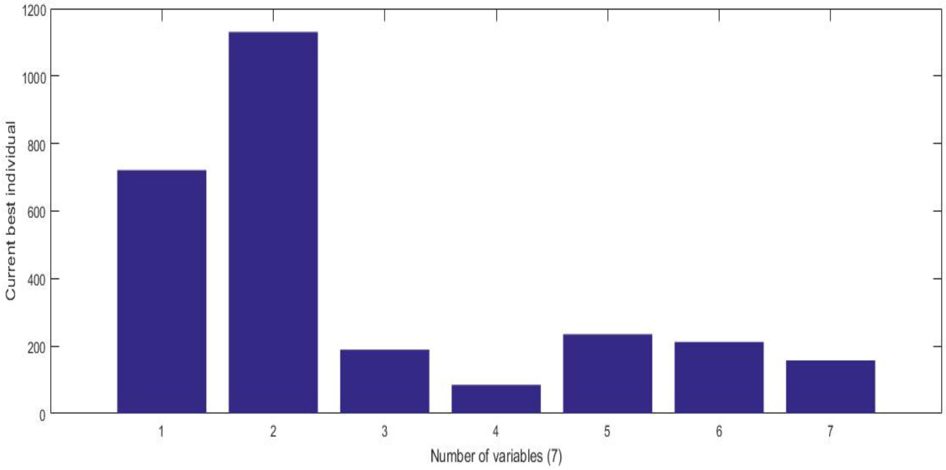

Fig. (9): Final Best individual Best, Worst and Mean Scores with Generation

According to optimized potential, maximum number of hydrokinetic turbines could be placed are determined and listed in Table (3).

Table 3: Optimized HK potential

Sr. No.	HKP Site	Bus no	Optimized Potential in kW	Required No of HK turbines
1	Ramjhula	3	721	23
2	Jok	7	1131	21
3	Haldogi	8	190	7
4	Simalkhet	9	85	3
5	Sirabhu	11	235	6
6	Vyasi	16	212	4
7	Amkholi	17	157	3
Total number of turbines to be installed				67

Total power generation hydrokinetic turbines installed at different nodes of distribution system during 5 % dependable flow is 2731 KW and 67 is total number of hydrokinetic turbines to be installed at different nodes as per Table (3).

Load flow is carried out in MATLAB 2016a for the assumed 33 bus radial distribution system by keeping hydrokinetic plants having capacity 721, 1131, 190, 235, 212 and 157 KW placed at nodes 3, 7, 8, 9, 11, 16, 17 respectively as distribution generation. The voltage profile improvement at different nodes of radial distribution system with and without placement of hydrokinetic turbines as distribution generation is compared and depicted in Fig. (10). It is clearly seen that voltage at node 18 has lowest voltage among nodes, which is improved to10.58 KV from 9.69 KV with voltage regulation from 11.9 % to 3.8% with placement of distributed generation. Most of nodes are seem to be suffered from more deviation from nominal voltage during peak load, which has been improved by placement of hydrokinetic plants at different nodes as distributed generation. Total voltage drop in the given distribution system was 0.2571 KV which gets improved 0.0902 KV. Thus, total voltage drop in the system in improved by 0.1669 KV after placement of hydrokinetic plants.

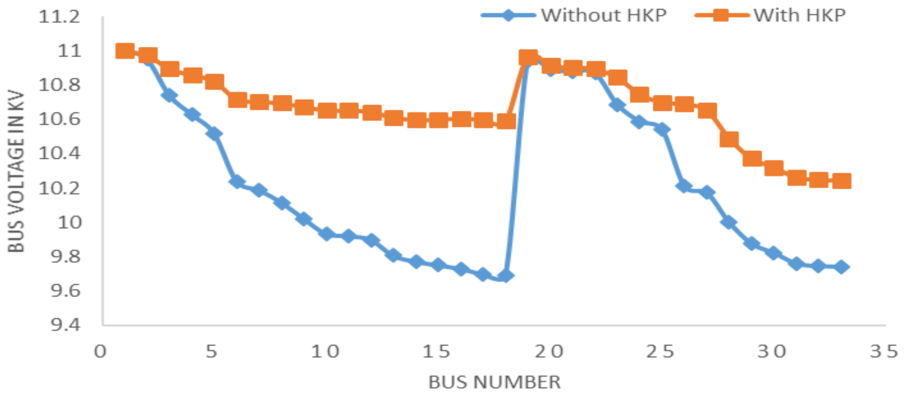

Fig.(10): Voltage Profile Improvement

The active power losses in branches of radial distribution system under study with and without placement of hydrokinetic plants are shown in Fig. (11). Without placement of hydrokinetic plants branches 1 to 5 and 27 to 28 had more active power losses compared to other branches. The highest active power loss was 71.94 KW in branch number 2 without placement of hydrokinetic plants. Total active power loss without placement of hydrokinetic plants is found to be 288.6 KW being 8% of total load. Placement of hydrokinetic plants decreases active power loss to 121 KW with saving of 167.6 KW during peak load. The active power loss is reduced at larger rate at branches 1 to 5 rather than branch number 27 and 28.

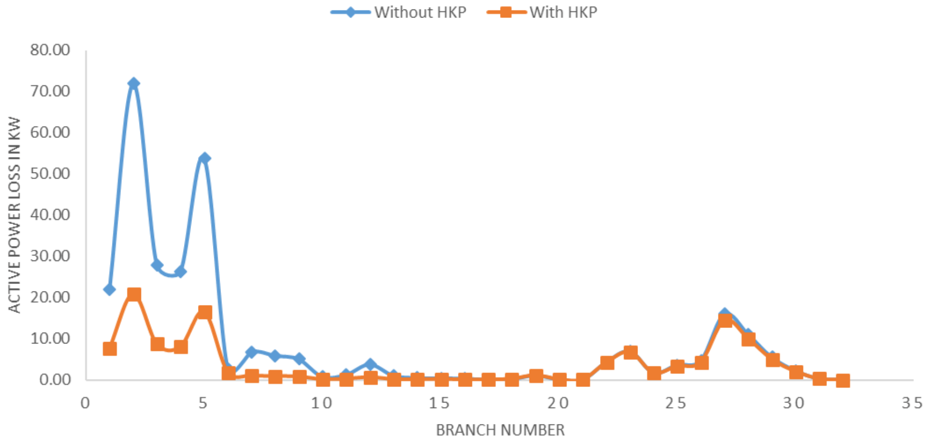

Fig.(11): Plot for Active Power Loss

Without placement of hydrokinetic plant, branches 1 to 6 and 27 to 28 had higher reactive power losses compared to other branches, 46.47 KVAR being the highest in branch number 5 and total reactive power loss amounting 191.81 KVAR in the distribution system under study. . Placement of hydrokinetic plants decreases total reactive power loss amounting only 87.27 KVAR with a saving of 104.54 KVAR during peak load hours. Net improvement reactive power loss is phenomenal in branch 1 to 6 rather than branch number 27 & 28. The curves showing effect of placement of hydrokinetic plant on reactive power loss is shown in Fig (12).

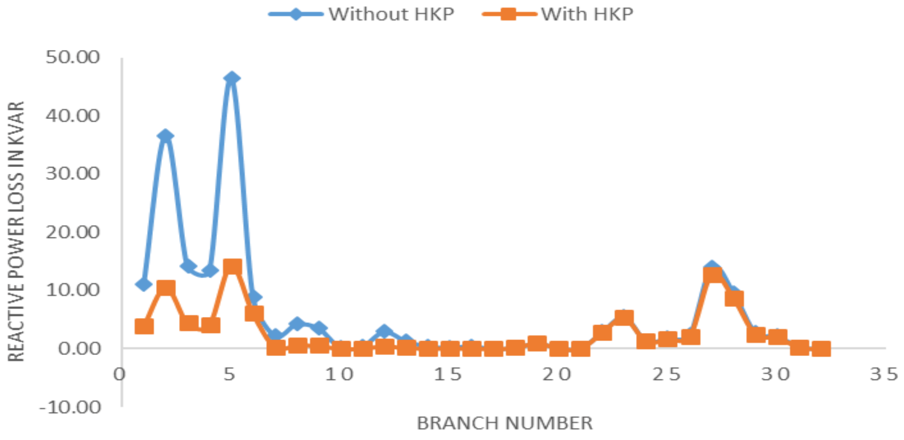

Fig.(12): Plot for Reactive Power Loss

The cost of saving during peak hour by placement of hydrokinetic plant is Rs 711.88 per hour as listed in table (4) considering the rate of purchase of electricity by Distribution Company per KWhr and KVAR to be Rs 3 and 2 respectively.

Table 4: Cost of saving by installation of hydrokinetic plant during peak hour

Sr. No.	Description	Quantity	Unit	Rate (Rs.)	Hourly saving (Rs.)
1	Energy saving per hour	167.6	KWHr	3	502.8
2	Reactive power saving	104.54	KVAR	2	209.08
Total saving during peak hour (Rs.)					711.88

Apart from savings listed in Table (4), placement of plant in distribution system will reduce transmission losses because the portion of load is supplied by hydrokinetic plant rather than far end situated other generating station.

IV Conclusion

Technically recoverable hydrokinetic potential has been determined with number of turbines and placement of turbine for hydrokinetic farming for the river segment along the radial distribution system under study. These potentials are optimized in the perspective of distribution generation achieving not only improved voltage profile but also saving in active and reactive power losses. It can be concluded that the hydrokinetic energy is more predictable being not intermittent and most suited for distribution generation in comparison with other renewable energy sources like solar, wing etc.

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