Design of Mini Grid for SHP Plants

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Abstract: The supply of power to remote rural areas in India from Small Hydropower Projects (SHP)/renewable energy power projects in cost effective and sustainable manner requires the optimum design of mini-grids. The present paper deals with the design of mini grids of nine SHP plants presently running in isolated mode only for 8 hrs/day wasting the energy of 16 hrs/day. Based on system layouts, transmission routing, line length and selection of conductor, 5 different alternates of mini-grids were developed to connect these SHPs together as well as with the nearby 33 kV grid substations located at approximately 15, 17 and 9 km from nearby SHPs in order to improve the load factor. The optimization of these alternates on the basis of the Break Even Point (BEP) has indicated that Alternate-V has been found as optimum alternative for the study area with shortest line length, low line losses and minimum capital investment for the mini-grid implementation.

Key words: Small Hydropower Project (SHP) station, mini-grid, remote rural areas, Break Even Point, India

Introduction

Over 1.6 billion people of the world have no access to electricity due to high capital cost required for extending the grid and the utility grid is hard pressed to meet the growing demand of urban areas with lowest priority to rural areas. The rationale behind the development of mini-grid for SHP and renewable energy based power plants is to supply power in cost effective and sustainable manner than grid/diesel based mini grids. Experience of developing countries has shown that hydropower mini-grids are the cost effective approach to supply electricity to rural areas rich in renewable resources. In hilly areas, a number of rivers and streams can be harnessed to produce electricity that can be used to electrify such remote rural areas away from utility grid. The SHP plants can produce cheaper and reliable power compared to diesel generators or high voltage grids. Local mini-grid can be designed for such areas to distribute the reliable and quality power from Small Hydropower Project (SHP) as well as from other renewable resources. The technology for SHP is not new, but is facing the challenge of supplying the power at very low annual running costs.

This paper presents a case study of Bageshwar District of Uttarakhand in India, where nine SHPs running in isolated operating mode were selected for the design of mini-grid. These SHPs are presently operated for eight hours per day only with the wastage of 16 hour/day of energy with very low load factor. The aim of the study is to design a mini-grid to improve the load factor of SHPs and supply the power to the consumers. The work, being presented, deals with the design and development of mini-grid in the above area to interconnect the SHPs with each other as well with the nearby 33 kV grid substation located at approximately 15, 17 and 9 km from nearby SHPs. The preparation of system layout of proposed area, design of different alternates of mini-grid based on transmission routing in the area and selection of optimum alternate for mini-grid are discussed in this paper.

Literature Review

Deshmukh and Bilolikar (2006) studied the feasibility of grid extension and distributed generation considerating biomass and diesel based generation options and BEP (break even point) based optimization suggested it as a cheaper option than grid extension. Monteiro *et al* (2005) have studied the impact of integration of distributed resources on electricity distribution using a spatial support system. Geographical information systems (GIS) was used by Zhou Quan *et al* (2002) to develop mathematical models of the substation location and capacity optimization and proposed a new multi-period optimal selection algorithm of substation that can determine the reasonable location, capacity and time of substation operation. Khator and Leung (1997) reviewed the models related to the planning of substations and/or distribution feeders under two major groups: planning under normal conditions and planning for emergency and found the power distribution planning as difficult to ensure substation capacity (transformer capacity) and feeder capacity (distribution capacity) to meet the load demands. A new methodology was developed by Monteiro *et al* (2005) for automated route selection for the construction of new power lines based on GIS considering the environmental constraint, operation and maintenance and equipment installation costs associated with the slope of the terrain crossed by the power lines. Jewell, Grossardt and Bailey (2006) developed a new method to reduce public opposition to new lines by way of public participation in transmission line routing decisions and hence the time needed for the approval of new line construction. A fast algorithm was presented by Tram and Wall (1988) to help select the proper conductors for feeder expansion plans including selection of optimal conductor type for each feeder segment to maintain an acceptable voltage profile along the entire feeder and minimize the capital investment and the cost of feeder losses. Urban, Bandars and Moll (2009) developed six different scenarios of rural electrification for the period 2005-2030 using a regional energy model (REM) to assess the effect of green house gases (GHGs), primary energy use and the costs and compared the business-as-usual (BAU) scenario with different rural electrification scenario based on electricity from renewable, diesel and the grid. The results indicated that rural electrification with renewable energy tends to be the most cost effective option. Kaundinya, Balachandra and Ravindranath (2009) have studied the modeling and analysis of economic, environmental technical feasibilities of both grid connected and stand-alone system as decentralized power options, which was restricted to annualized life cycle cost (ALCC) methods.

The literature reveals that no work has been done on the design of mini-grid in India for connecting all the cluster SHPs and other renewable energy power projects together as well as with the main grid, wherever available, to electrify the remote rural areas not connected with utility grid. Therefore, the design of the of mini-grid for nine SHPs of Bageshwar District has been undertaken and the results are presented in this paper.

About the Study Area

The map of Bageshwar District was prepared by topographic maps of the district using ERDAS IMAGINE Arc view GIS 3.2 software. The project area includes all the SHP plants where mini-grid is to be installed. The map has been used to plan and design the process and provide a framework to collect the necessary data. There was a need of the area map with location of mini-grid, which would help to prepare different layouts that can be compared in terms of cost and reliability giving an optimum transmission line routing and layout for the distribution line Urban, Bandars and Moll (2009).

The map helps to locate the SHPs and load centers. Mini-grid is designed for SHPs and finally connected to the main grid so that load on main grid could be reduced. This also includes other landmarks like hilly areas, water bodies, dense forest, trails, roads, streams, village community, etc. Maps were drawn on a scale such that the distances could be used, later on, to calculate the length of transmission line, conductor size, pole locations, etc. The maps were prepared using topographic map, aerial photographs, satellite imaginary and GPS.

Procedure for Preparation of Map

Figure 1 shows the various steps in the preparation of map of Bageshwar District of Uttarakhand with location of SHPs and mini-grids. The topographic maps of nine SHP sites of Bageshwar District along with latitudes and longitudes are available and the study area comes on the twelve topographic maps. The latitudes and longitudes, location of the SHP sites and existing substation of Uttarakhand Power Corporation Limited (UPCL) Grid are given in Table 1.

Name of SHPs, Existing Substation	Installed Capacity (kVA)	Block	East Longitude	North Latitude
Kanolgad SHP	150	Kapkote	79°46′00″	29°56′00″
Lamabagad SHP	200	Kapkote	79°45′19.6″	29°57′17.4″
Toil SHP	62.5	Kapkote	79°53′00″	30°06′00″
Leti-I SHP	62.5	Kapkote	80°03′00″	30°01′00″
Leti-II SHP	62.5	Kapkote	79°49′30″	30°04′00″
Lathi- I SHP	125	Kapkote	80°04′00″	29°55′30″
Lathi – II SHP	125	Kapkote	80°03′00″	30°02′00″
Ratmoli SHP	62.5	Bageshwar	79°51′00″	29°46′00″
Satyeshwar SHP	62.5	Bageshwar	79°49′00″	29°46′00″
Kapkote Substation	3.0 MVA	Kapkote	79°54′00″	29°57′36″
Kafligaiy Substation	4.5 MVA	Bageshwar	79°45′00″	29°43′48″

Table 1. Location of SHPs sites and Existing Substation of UPCL

The latitude and longitude of a topographic map is given at four points as shown in Figure 2, on the basis of which the topographic maps were geo-referenced.

All the 12 topographic maps were geo-referenced using latitude and longitude data.

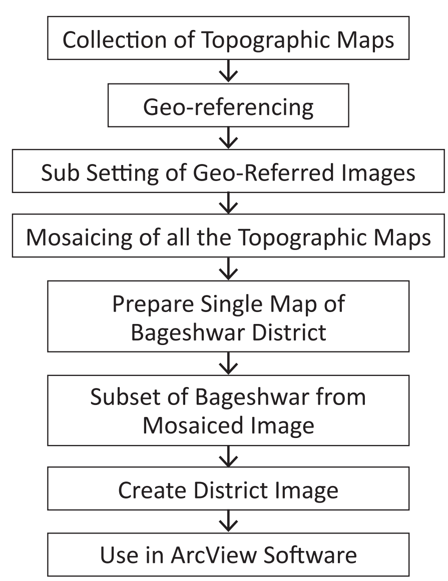

Figure 1. Steps in the Preparation of District Map and Location of SHPs & Mini-Grids

System Layout

The map was used to provide a base on which the layout of the mini grid including the transmission line routing was drawn. In hilly regions like Bageshwar, the transmission line routing is relatively tricky and difficult task. Compared to plain areas, the elevation level in hilly area varies considerably, thereby creating the problem of routing transmission as well as distribution lines. On the topographic map, the elevation of the region is shown by

Figure 2. 53N/8 Topographic Map Showing Four Corners

contours, which are the base lines showing the elevation of the surface points. In such cases, two methods are used to draw the transmission line routing:

(a) To survey and prepare the map by surveying instruments and estimating the optimum value or the shortest feasible path for the transmission line routing. This approach is very difficult and time consuming, and there are likely chances of getting more length of transmission line resulting in high cost and more line losses.

(b) Another approach is to use the software to generate Digital Elevation Model (DEM) by ArcView of the area of interest, and carrying out the transmission line routing by visual sense of the DEM. A comparison of different alternatives of connecting the SHPs provides optimum option for line routing. The cost as well as the technical feasibility of the routing of the transmission line can be analyzed without real survey. Using ArcView, transmission line routing is very cost effective and time saving. Since there is no need to survey the area, and once the digital data are generated, it can be used for long period of time.

The following inputs were used for determining the elevation of the points and spot heights:

i. Values of contours and spot heights of topographic map
ii. GPS (Geographical Positioning System) receivers
iii. Total station (surveying instrument)

Total station has been used to provide the elevation by manual measurements at site. Using the topographic map, the values of contours as well as the spot heights were obtained directly.

Procedure for the Preparation of System Layout

System layout of mini-grid was prepared in ArcView using the following steps:

(a) The raster image of Bageshwar District was imported in ArcView and contours were digitized to get digitized map as shown in Figure 2.

The existing grid of UPCL with substations and SHPs sites is given in Figure 3, for which the mini-grid is to be designed.

TIN (Triangular Irregular Network) model or digital elevation model was created according to the elevation of contours as shown in Figure 4. The accuracy of TIN model depends upon on the contour elevation difference, which is taken as 200 m.

(b) Digital Elevation Model (DEM), a type of raster GIS layer, represents the world as a regular arrangement of locations. In DEM, each cell has a value corresponding to its elevation. The arrangement of locations regularly permits the raster GIS to infer many interesting associations among the locations. One of the most powerful applications of DEMs is adding synthetic hill shading to the maps so that the map reader may see the relationship between terrain and other things.

A Raster GIS can calculate many useful derivatives of elevation, slope and Aspect- the direction of slopes. The volume within area as well as the volume above and below of a particular elevation can be calculated. DEMs has been used to create 3-D scenes or to create contour (see www.gsd.harvard.edu/gis/manual/dem/index.htm). The DEM of the area is shown in Figure 6.

(c) ArcView GIS 3-D Analyst has been used to create three-dimensional views directly using GIS data as shown in Figure 6.

Transmission line routing has been done by visual sense by finding the length of each possible connection. The length of line is directly related to the installation cost of mini-grid. The DEM of existing grid and all the routings of mini-grid is shown in Figure 7 and 8.

On the basis of the above analysis, the five different layouts were prepared using different line placing arrangements of mini-grid and these layouts are named as Alternate –I, II, III, IV and V and are shown in Figure 9 through 13, respectively.

Estimation of Line Length and Selection of Conductor

The design of micro-grid is based on distribution voltage level that can be selected on the basis of mode of power transfer and the distance of transfer. The voltage level is increased to reduce the transmission losses. The system voltage can be classified either by system use or voltage range. The voltage level from primary/secondary distribution system has to be matched with the system voltage. Nominal system voltages are classified as per standard (Indian Standard 1985/2002). The cost of lines is the deciding factor in the choice of voltage. It is a rule of thumb that the voltage of line is taken as 0.6 kV/km of length of line. The most common voltage for short distance lines is 11 kV, while 415/240 V is used for distribution to consumers (ibid.). Therefore, 11 kV is selected as the voltage for micro-grid to be designed.

The most commonly used conductor for distribution of power upto 11 kV is aluminium conductor steel reinforced (ACSR). All aluminium conductor (AAC) galvanized steel, copper conductors and rabbit conductors are based on the level of power to be transmitted, length of line, line voltage, permissible voltage regulation and mechanical strength.

The conductor is selected on the basis of maximum kW-km limit for different alternates and for each segment of grid line. Analysis has indicated that the rabbit conductor has been selected for the present loading for 56.52 km out of 93.82 km conductor length. The length of rabbit conductor has been increased to 89 km to accommodate future power generation in the area. Therefore, the micro-grid has been designed considering rabbit conductor for all alternates. The overall diameter of the rabbit conductor is 10.05 mm, with a resistance of 0.5426 Ohm/km.

For calculation of load flow and reliability, the bus, line, connectivity, reliability, generator and load data were calculated on the basis of system base voltage and base apparent power.

Bus data

Layout of Figures 8 to 12 show 18 buses in the system, with bus data comprised of bus identification number, name, state, and base voltage bus category. These data were used for calculation of reliability program and load flow using the software program. The bus state '0' means ON, '1' means OFF. Bus category '1' means generator bus, '2' means load bus at which reliability is evaluated.

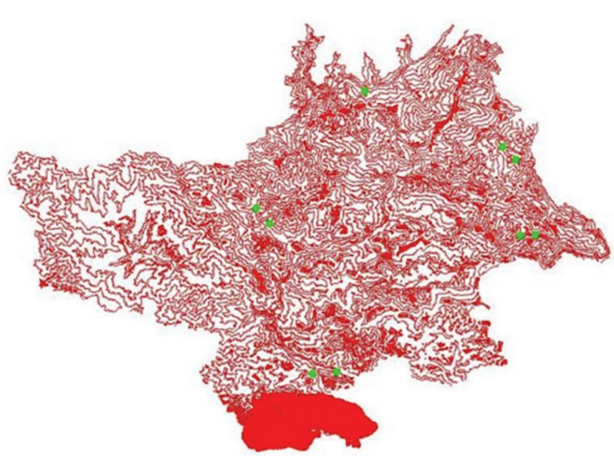

Figure 3. Digitized Contours and Location of SHP Sites in Bageshwar District

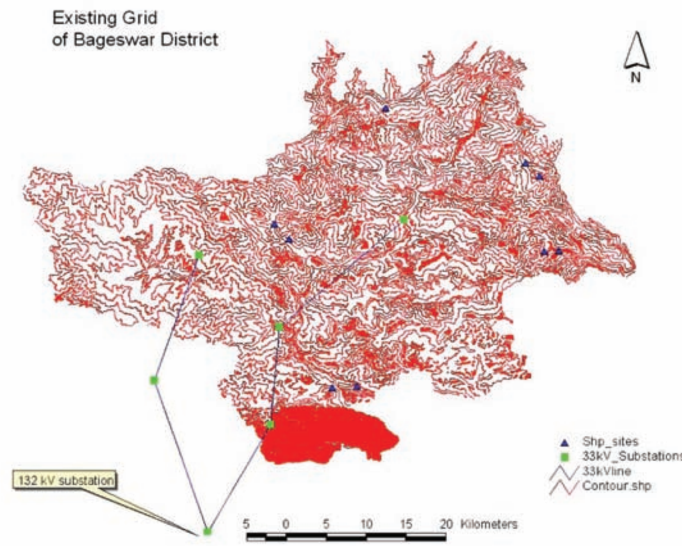

Figure 4. Existing Grid of UPCL with Sub-Stations in Bageshwar District

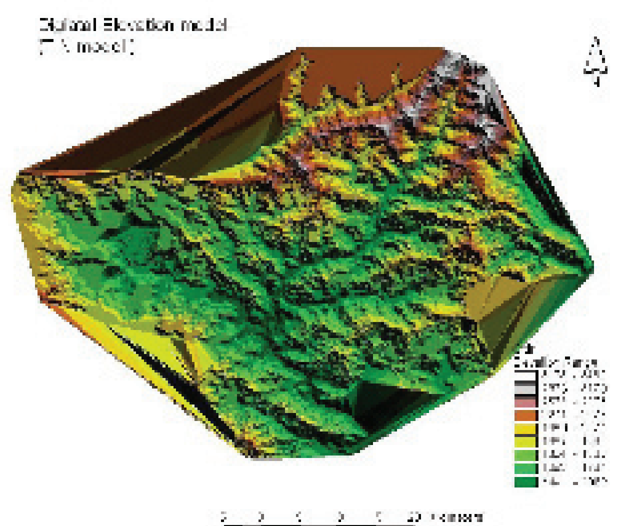

Figure 5. TIN Model or 3-D Model of the Area of Interest

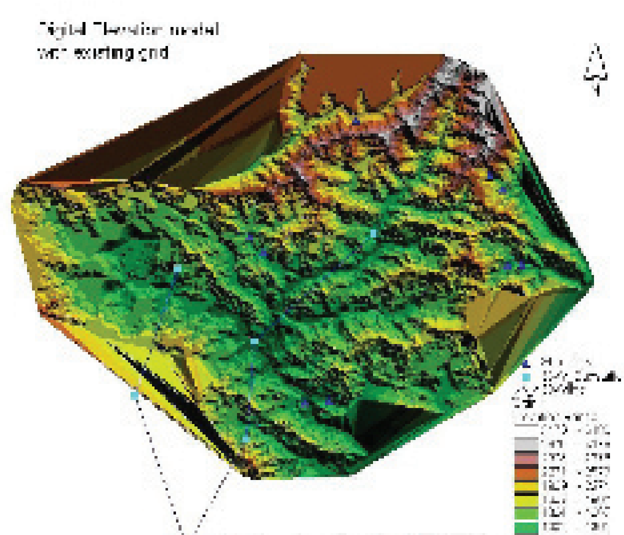

Figure 6. 3-D View of Existing Grid and Location of SHPs.

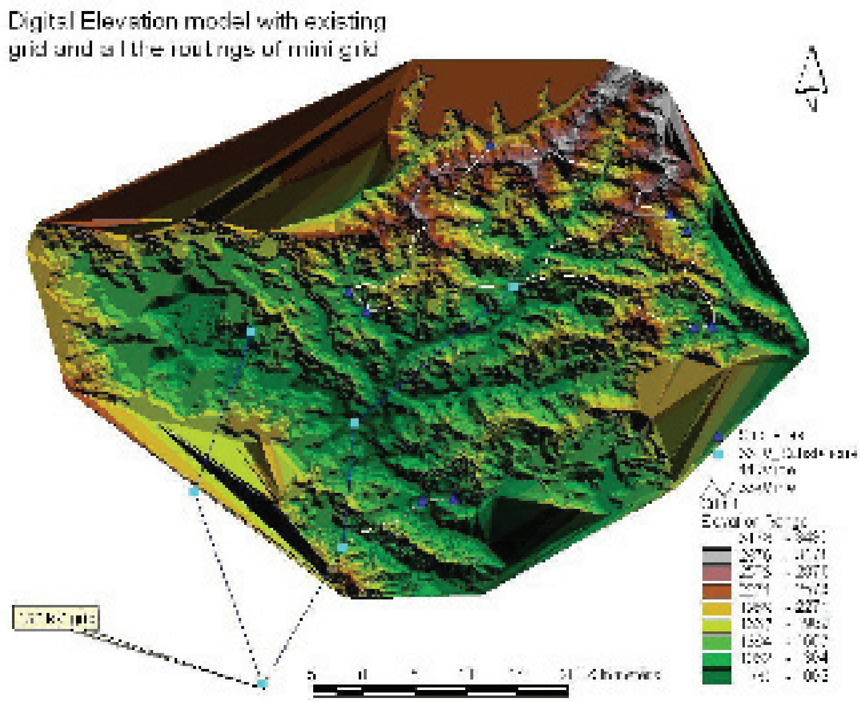

Figure 7. 3-D View of Mini-Grid with Existing Grid

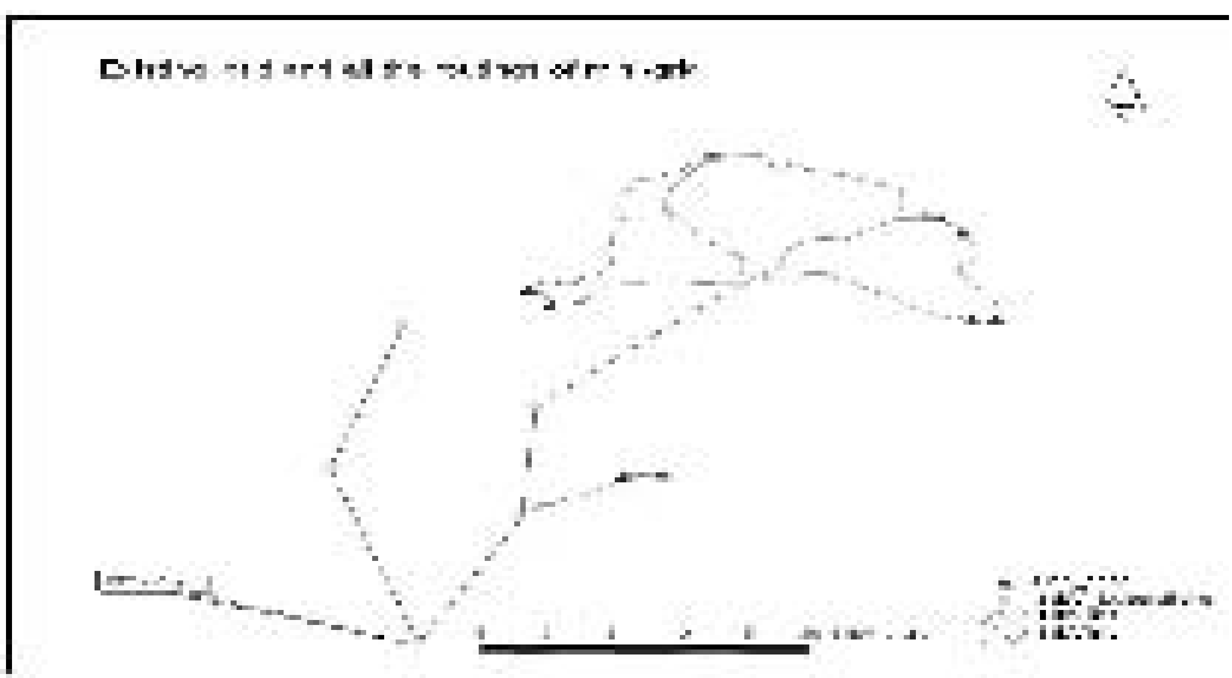

Figure 8. Mini-Grid Routing with Existing Grid.

Line data

Line data have line parameters; i.e., line resistance (per unit), line reactance (per unit) and line susceptance (per unit), base rating sending and receiving end of the bus. Line parameters were calculated using standard equations (AHEC/IIT 2007).

Similarly, per unit resistance, reactance and susceptance were calculated for 33 kV line raccoon conductors having overall diameter of 12.3 mm and resistance of 0.3622 Ω /km. The line configuration used was as per IS standard (Indian Standard 1985/2002).

The resistance (Rpu), reactance (Xpu) and susceptance (Bpu) in per unit are calculated as 3.326 $\times$10-3, 3.403 $\times$10-3 and 3.366 $\times$10-4 /km, respectively, and were used to calculate per unit of resistance, reactance and susceptance for each line and input in file format as required by the software or program.

Connectivity data

Connectivity data have sending end bus number, receiving end bus number, type of the line whether single directional or by directional. A component identification number in the data line is given for identification. The status of the line, whether in service or out of service, is also indicated.

Generation and loading data of bus

These data have type of bus; i.e., slack bus, generator, load or other type bus. For generator and slack bus, active, reactive and maximum active power generated in MW, MVAR and MW, respectively, is required. For load bus, active and reactive power consumed on the bus is provided in the data.

Reliability analysis

Reliability data are concerned with the failure data and the repair time. The temporary failure and maintenance

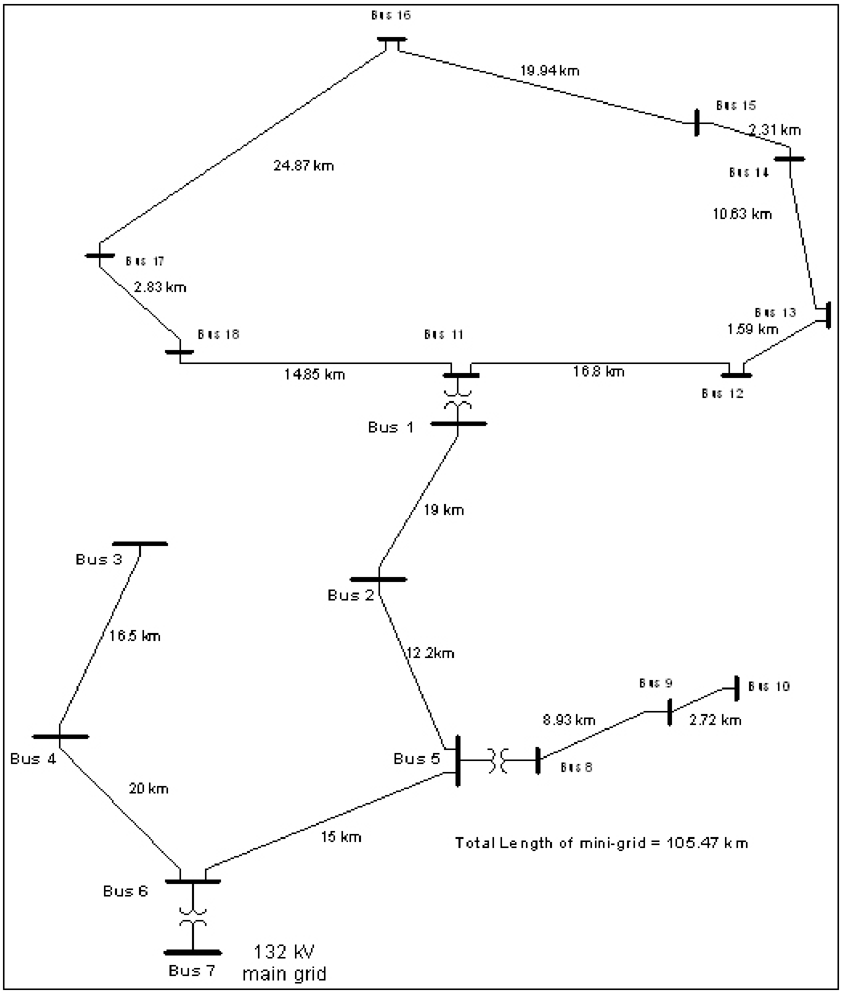

Figure 9. Alternate-I of Mini-Grid

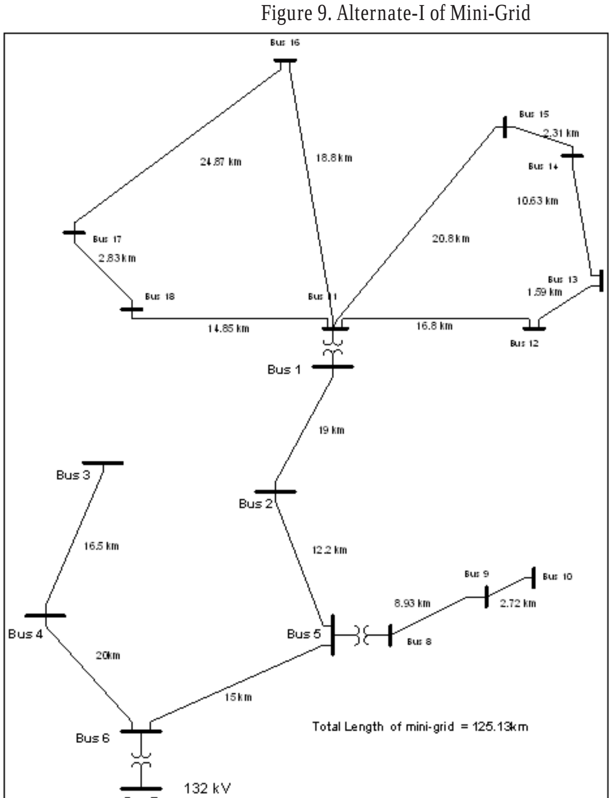

Figure 10. Alternate-II of Mini-Grid

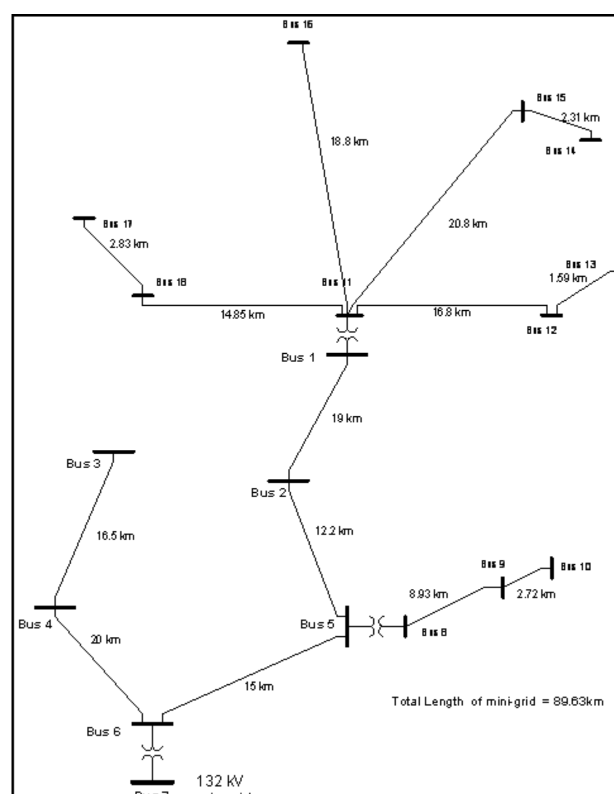

Figure 11. Alternate-III of Mini-Grid

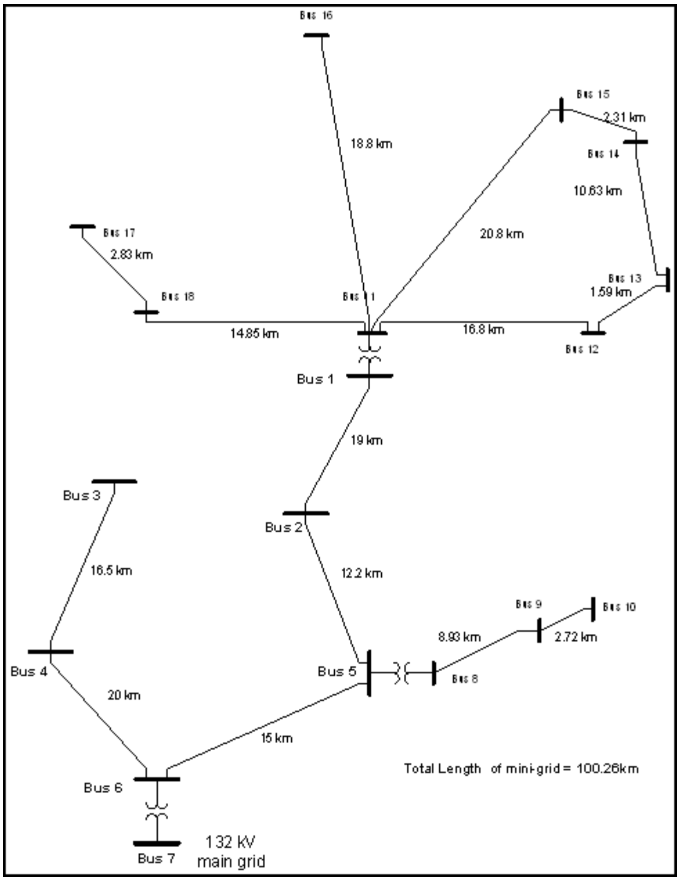

Figure 12. Alternate-IV of Mini-Grid

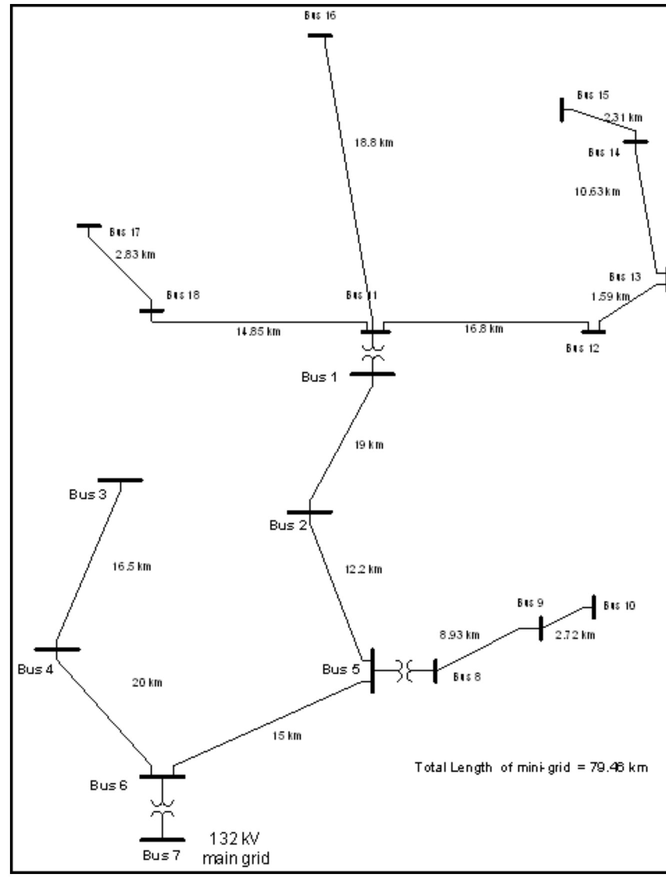

Figure 13. Alternate-V of Mini-Grid

outage are ignored as partial loss of continuity is calculated. All other type of outages is same in each alternate so they are taken as zero. Line failure depends on the length of the line or line voltages. For high voltage lines, the failure rate is less as compared to low voltage lines. The reliability data are taken as the failure rate per kilometer of the particular voltage level so that the failure rate is increased with increase in the length of the line. By simply multiplying the total length, the whole reliability can be calculated.

Reliability is calculated on the load bus numbers 2 and 3. The other loads are on same generator buses of mini-grid. There is no difference with reliability of different alternates as there is no failure on these loads when line is failed. As the system is connected to the grid supply, the reliability of the system on these two points is also same for all the alternates. The reliability indices as calculated by the Transmission and Distribution Reliability Evaluation Program (TDREP) are given in Tables 2, 3 and 4.

The indices are the same for all alternates at these two points. The program calculates the reliability indices and unserved energy at the two load points.

Calculation of annual energy losses

The line lengths of all five alternates are calculated by GIS software with help of 3-D topology of area and line routing as given in Table 5. Alternate-V requires minimum line length.

For calculation of energy losses in the mini-grid, the load flow is done by PSAT software. The input data for alternates-I have been taken from (AHEC/IIT 2007). Then, the data files for other alternates were made in a similar manner. The energy losses were calculated for healthy as well as interrupted system. The outage combination is taken as only one line failure at a time. The annual outage time is calculated on the basis of length of transmission line, longer the length, higher the annual failure rate so more outage time. The per km failure rate of 11 kV line is taken as constant. And for energy loss calculation, the repair time is taken as 10 hour for any failure of line.

Finally, the total annual transmission energy losses were calculated by adding energy loss at the time of failure and transmission energy loss for healthy system. The results are given in Table 5, which shows that Alternate-V has the maximum energy loss of 752.4 MWh. All other calculations were done in a similar manner.

The capital cost of line is taken as Indian Rupees (INR). 0.35 million rupees considered as proportional to the length (CEA/MOP 2008). The running cost includes interest on capital, depreciation and operation and maintenance cost. The running cost of all the alternates is given in Table 6.

The rated supply of nine SHPs is 730 kW; but the SHPs are running as stand-alone for eioght hours/day for lighting load only, thereby wasting huge hydropower potential. The potential can be tapped while supplying the power through mini-grid as well as connecting the SHP to 33 kV grid sub station available at 15, 17 and 9 Km from nearby SHPs. In areas too far away from utility grid, the load factor of these SHPs by providing livelihood earning technologies that can be operated during low load period.

The annual energy that can be supplied to the grid after mini-grid installation has been calculated as 4263.2 MWh taking into account the 16 hrs/day operation (which was earlier going waste). Table 7 gives the annual revenue generation @ INR 2.40 per kWh available from all the alternates of mini-grids after grid installation.

Optimization

The break-even point (BEP) can be defined as the point at which an investment starts generating a positive return or the point at which the total costs (discounted) becomes equal to the total revenue (discounted). The break even analyses can be used to calculate the payback period or the time required to get break-even point. The BEP analysis is based on the investment of transmission lines only considering the interest rate of 11%. For optimization, the BEP has been calculated and compared to each other and the results are reported in Table 8, which shows the Alternate-V as the optimum design of mini-grid in terms of minimum length requiring less capital investment. The BEP for Alternate-V has been calculated as 6.5 years, the minimum of all the alternates considered above.

ID Number of Component Out	Out Rate O/yr	Average Duration (hrs)	Annual Duration (hrs/yr)	Average Load Disconnected (MW)	Energy Lost (MWh/yr)
6	0.593	10	5.93	1.090	6.464

Table 2. Partial Loss of Continuity

Name of Busbar	Probability of Service Interrupted	Expected Frequency of Service Interruption	Service Interruption Time (hrs)	Total Interruption Time/Yr (hrs)	Expected Unnerved Load (MW)	Expected Unnerved Energy (MWh)
Bus 2	$0.6769e^{-3}$	0.593	10	5.93	1.09	6.464
Bus 3	$0.6769e^{-3}$	0.593	10	5.93	0.49	2.906

Table 3. Bus Bar Reliability Indices

Indices:	Value:
Service failure probability	$0.13539e^{-2}$
Service failure occurrence	1.19 /yr
Service failure hours	11.86 hr/yr
Average load not supplied	0.79 MW
Unserved energy	9.3694 MWh/yr

Table 4. System Reliability Indices

Network System	Line length (km)	Losses (MWh)
Alternate - I	105.47	745.50
Alternate - II	125.13	710.4
Alternate - III	89.63	735.65
Alternate - IV	100.26	728.76
Alternate - V	79.46	752.40

Table 5. Line Length and Annual Energy Loss in Different Alternatives

Network connection	Line Length (km)	Capital cost (million INR)	Annual interest 11% (million INR) (a)	Depreciation 1% (million INR) (b)	O&M 1.50% (million INR) (c)	Variable annual cost (million INR) (a+b+c)
Alternate - I	105.47	36.915	4.061	0.369	0.553	4.983
Alternate - II	125.13	43.796	4.818	0.438	0.656	5.912
Alternate - III	89.63	31.370	3.451	0.314	0.470	4.235
Alternate - IV	100.26	35.091	3.860	0.351	0.526	4.737
Alternate - V	79.46	27.811	3.059	0.278	0.417	3.754

Table 6. Capital and Variable Cost for All Five Alternates

Network Connectivity	Total Energy Supplied to Mini-Grid (MWh)	Annual Energy Losses (MWh)	Total energy Supplied to Main Grid (MWh)	Annual Revenue Generated (Million INR)
Alternate I	4263.2	745.5	3517.7	8.44
Alternate II	4263.2	710.3	3552.9	8.53
Alternate III	4263.2	735.6	3527.6	8.47
Alternate IV	4263.2	728.7	3534.5	8.48
Alternate V	4263.2	752.4	3510.8	8.43

Table 7. Revenue Generated Annually

Alternate	Break-even Points
I	After about 12 years
II	After about 20 years
III	After about 8 years
IV	After about 10 years
V	After about 6.5 years

Table 8. Break-Even Point for All the Alternates

The total annual energy supplied to the main grid by various Alternates (Table 7) indicates that though annual energy supplied to the grid is less (3510.8 MWh) compared to other alternates but the capital investment and BEP is considerably less making it the best alternative for the study area.

Results and Discussions

Based on the results presented above, the break-even point method has been used to optimize various alternates. An optimized system requires minimum time for break-even point to occur. The break-even points for different alternates are given in Table 8, which shows that Alternate-V is the optimum alternate, as the line length in this alternate is shortest requiring minimum capital investment. Further, mini-grid (Alternate-V) and implementation of optimum design can be expected to be cost effective for Bageshwar District of Uttarakhand State of India. The BEP of Alternate V has been computed as 6.5 years, lowest of all alternatives. The supply of power through the design of micro-grid of Alternate–V has been further shown to reduce CO2 emission of 1193 tons/million units of electricity generated, which is a substantial reduction under CDM scheme (Inversin 2000).

Therefore, the mini-grid design of Alternate-V has been suggested for installation for Bageshwar District of Uttarakhand State for connecting all the nine SHPs with each other and with nearby 33 kV grid substations located at approximately 17, 15 and 9 kilometers from nearby SHPs. The implementation of this mini-grid design based on Alternate-V will definitely improve the load factor of all power houses and at the same time enabling the local consumer to get more power for more time. In areas where utility grid is too far from clusters of SHPs, it is proposed to put various livelihood activities like grinding, wood carving, welding, carpentry machines, facilities to repair electrical/electronic devices, a computer center, and a motor operated rope-way for transport of material from one place to the other in hilly areas, etc. These facilities would help to improve the loss factor of off-grid SHP as well enable the people to generate financial recovery to raise their economic standards.

Conclusions

Since the grid is not accessible to remote rural areas due to its high capital involved in its extension and therefore, SHPs or other renewable energy projects may supply the power to such areas in cost effective and sustainable manner. The power supply can be made through suitably designed mini-grids. The Bageshwar District of Uttarakhand State, where nine SHPs are running in isolated mode only for eight hours/day wasting energy of 16 hours/day has been selected for designing the mini-grid. Based on the system layouts and transmission line routing, five different alternates of mini-grid have been developed to connect these SHPs together as well as with the grid in order to improve the load factor. The optimization based on the break even point (BEP) has found Alternate-V as the optimum alternative for the mini-grid implementation of study area. BEP of the optimum Alternate-V has been found as 6.5 years (at interest rate 11% per annum) with shortest line length requiring minimum capital investment.

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