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Optimal Conductor Reinforcement and Hosting Capacity Enhancement for Radial Distribution Line of Beni Feeder

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Abstract

With the high penetration of DG, the operational limit violation problems can occur in the power system if it exceeds the hosting capacity (HC). One of the measures for increasing hosting capacity would be upgradation of conductor. In this paper, an existing radial distribution system of Beni feeder, Milanchowk substation is studied under various loading conditions. The conductors are upgraded with the conventional optimization tool and feeder reinforcement using SSO, and the effect on system loss, voltage and hosting capacity were analyzed. The loss is minimum for the reinforcement with SSO. The hosting capacity was calculated with generation ranging from 25% to 200% of the peak load with existing, conventionally optimized and reinforced feeder are 55%, 65% and 87% respectively. Along with the higher hosting capacity and lower loss, the reinforcement approach is also supported by the financial analysis.

Keywords

Distributed Generation, Conductor Reinforcement, Hosting Capacity, FSBS, SSO

1. Introduction

Nowadays, with the development of the DG technologies like wind, PV, and micro-hydro (in a country like ours), the conventional direction of the power system has changed. Along with the technical, economic, social, and environmental benefits associated with the integration of the DG to the grid, there are some problems esp. with the excessive DG penetration [1]. Such problems include the operational violation limits with the exceeding of hosting capacity(HC).

HC refers to the maximum capacity of DG that can be integrated with the grid without adversely impacting reliability, quality of power, safety, or other operational criteria without any significant infrastructure upgrades [2]. The hosting capacity for any feeder depend upon some factors including conductor size, load distributions and mainly the location of DG. The effective method for the determination of HC should consider the outcomes with centralized DG or highly distributed DGs. As, a large number of DG at significant capacity can also have momentous impact on the distribution system. The location of a large centralized DG in distribution system has shown a significant but widely varying impact. The HC of the system is calculated concerning performance indices. With the greater level of injection of power in the network, for the technical limitations on the system's hosting capacity, two major limitations needs to be concerned[3]: Voltage and Current. The first is represented by the bus voltages of the system and the other with the loading capacity of the lines and cables.

After the investigation of different factors that affect the distributed hosting capacity, it is concluded that Volt/VAR Optimization, feeder reconfiguration, PV power factor setting and conductor upgradation approaches can be used to increase distributed PV hosting capacity [4]. The effect on the hosting capacity with the conductor upgradation [5] has been studied in this paper for the Beni feeder of Milanchowk substation. The selection of the conductor has been followed and compared for two methods: conventional optimal conductor selection approach and Feeder reinforcement approach using a bio-inspired salp swarm algorithm (SSO) [6] [7]. Moreover, with the financial analysis, the best conductor selection methodology is determined.

2. Material and Methods

Beni feeder was taken as consideration for the analysis.The feeder has the peak demand of 2.03 MW and 39km and 106km radial and total length respectively.With 131 total bus and 86, 3-phase transformers, XLPE, Dog, Rabbit and Weasel conductors are present in the feeder.

The system has been analyzed under the peak conditions (100% load), normal conditions (50% load) and considering future conditions (150% load) for the conductor replacement and determination of hosting capacity.

2.1 Load Flow Analysis

Load flow analysis has been performed with the Forward Sweep Backward Sweep method (FSBS) [8] [9]. With the forward sweep, the voltage drop is calculated with the update of current flow and with backward sweep the bus voltage is updated. The method forms with the injection of bus in branch current matrix and branch current in bus-voltage matrix. For the distribution network, the equivalent current injection based model is more practical [10] [11]. For ith, the load S_i can be depicted as

$$S_i = (P_i + jQ_i) \;\; i = 1...N \tag{1}$$

The injected bus current [I] and branch currents [B] are expressed in general form with respect to bus-injection to branch-current (BIBC) matrix as:

$$[B] = [BIBC][I] \tag{2}$$

Similarly, the relationship between branch currents and bus voltages in accordance with branch-current to bus-voltage (BCBV) matrix can be written as:

$$[\Delta V] = [BCBV][B] \tag{3}$$

From Eq.2 and Eq.3 , the bus voltage can be represented in accordance to the above matrices and bus current as:

$$[\Delta V] = [BIBC][BCBV][I] = [DLF][I] \tag{4}$$

And at the k-th iteration, the corresponding current injection can be expressed as:

$$I_i^k = I_i^r(V_i^k) + jI_i^i(V_i^k) = \left(\tfrac{P_i+jQ_i}{V_i}\right)^* \tag{5}$$

where V_i, I_i, P_i and Q_i are the bus voltage, equivalent current injection, real and imaginary components of power associated with current injection of ith bus at the k_{th} iteration respectively.

The voltage at each iterations are updated based on Eq.6.

$$[\Delta V^{k+1}] = [DLF][I^k] \tag{6}$$

2.2 Conventional Optimal Conductor Selection Approach

In the conventional optimal conductor selection approach, the optimal size at each section are calculated based on the total investment cost and losses. For the conductor of type y for feeder x, the total cost can be expressed as:

$$C^{total}(x,y) = C^{loss}(x,y) + C^{inv}(x,y) \tag{7}$$

The C^{loss} is calculated in terms of active power loss under the peak conditions (C_{loss}): calculated from the load flow, loss factor (LSF) and cost of energy loss (k_e) with annual hours (T) is represented with:

$$C^{loss}(x,y) = P^{loss}(x,y) * k_e * LSF * T \tag{8}$$

Also, C^{inv} is calculated with respect to the interest and depreciation factor (IDF) which depends on the factors: interest rate (i), lifetime of conductor (F), sectional length (l) and the cost on investment of each unit length (IC), thus:

$$C^{inv}(x,y) = IDF * l(x) * IC(y) \tag{9}$$

where,

$$IDF = \frac{i(i+1)^F}{(i+1)^F - 1} \tag{10}$$

For the lines with smaller resistance and area are replaced with the higher ones and vise versa. Although it is acceptable for the initial planning stages, for the existing scenario it is not practical to replace the existing conductor with a smaller conductor.

2.3 Feeder Reinforcement Approach

The major idea with feeder reinforcement approach is to reduce the total cost as the cost of investment would oppose the cost of loss. With increase in one the other decreases and vice versa [12].

Feeder Reinforcement Index (FRI), which illustrates the difference between sectional current and optimum conductor branch sizes, is used as the sensitivity index to prioritize the reinforcement bases on investment capabilities. FRI can be calculated as in Eq.11:

$$FRI = C^{loss}(x,y) - C^{inv}(x,y) \tag{11}$$

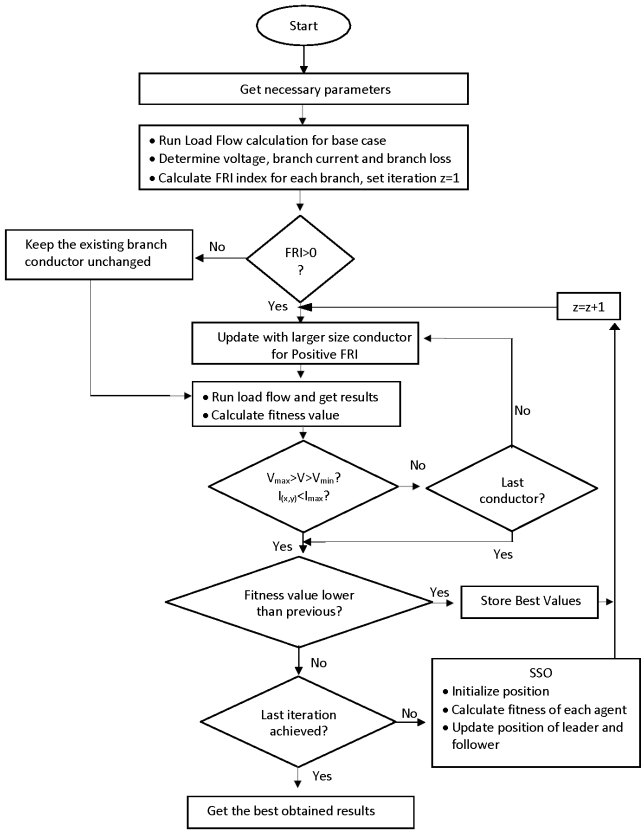

Figure 1: Methodology for conductor selection

With the salp swarm optimization (SSO), the conductor reinforcement of the selected 11kV system is determined. The selection of the conductor size can be obtained with the objective function expressed as:

$$Objective\,Function = minimum(C_{loss,t} + C_{inv,t}) \tag{12}$$

where, $C_{loss,t}$ and $C_{inv,t}$ are the sum of cost of loss and investment of all the sections. The three constraints are considered: bus voltage, branch thermal capacity and FRI to assure the acceptance with the voltage and thermal limits for the system.

$$V_{min}(m) \leq |V(m)| \leq V_{max}(m) \tag{13}$$

where, $V_{min(m)}$ and $V_{max(m)}$ are the maximum and minimum bus voltages, and for the peak time load flow are considered to be 0.9pu and 1.05pu respectively and 0.95pu and 1.05 pu for normal loading conditions.

To avoid the overheating due to overloading, the current through the section must be lower than the thermal capacity of the conductor i.e.

$$|I(x,y)| \leq I_{max}(y) \tag{14}$$

The action of reinforcement is determined based on the value of FRI as follows:

$$action = \begin{Bmatrix} Reinforce\ the\ feeder,\ if FRI > 0 \\ Keep\ the\ existing\ size,\ otherwise. \end{Bmatrix} \tag{15}$$

2.4 Optimal DG Location and Tool

The optimal location of DG was selected among the bus with minimum active power loss with DG capacity 100% of the peak load based on the peak load i.e. 100% loading conditions.

For the overall process, the programming was done with python programming language.

3. Results and Discussion

3.1 Base Case

The load flow was performed for the existing system as base case. From the Figure 2 it is evident that the minimum feeder voltage during the 50%, 100% and 150% loading conditions are 0.899, 0.773 and 0.567 pu respectively. So, with the existing infrastructure, the voltage of the system is expected to drop significantly at the higher loading conditions.

Figure 2: Bus Voltage with different loading for base case

The loading of each branch is presented in Figure 3 at different loading levels. It is illustrated that some line sections are overloaded at 150% loading while the other sections are below the allowable current carrying limit at other loading conditions.Due to lower loading, the current of some branch are much lower.

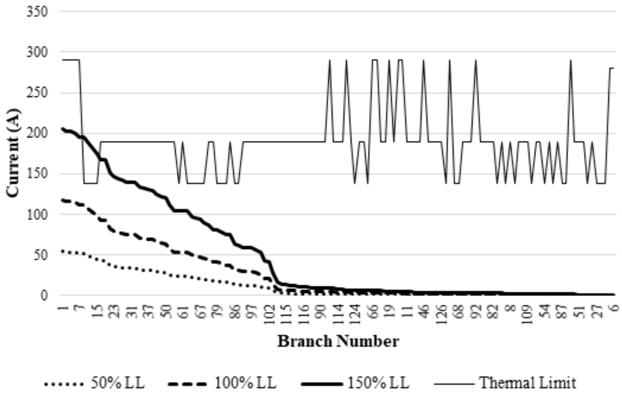

Figure 3: Branch Current with different loading for base case

The loss at the 50%, 100% and 150% loadings are 49.8kW, 248.38kW and 869.17kW respectively.

3.2 Conventional Optimal Conductor Selection

With the optimal conductor selection, the changes need to be made to the existing feeder is tabulated in Table 1. Since the construction of new Dog circuit is more economical than upgradation to Wolf, the Dog conductor is upgraded to double-circuit.

Table 1: Conductor selection with conventional method

S. N.	Previous Conductor	New Conductor	Length (km)
1	Weasel	Rabbit	9.267
2	Rabbit	Weasel	56.020
3	Rabbit	Dog	9.575
4	Dog	Rabbit	12.850
5	Dog	Dog-DC	3.307

The bus voltages in the feeder with the optimal selection of size of the conductor is presented in Figure 4. There has been some improvement in voltage level as compared to the existing scenario, however the minimum feeder voltage under different line loading for optimized scenario is almost low as 0.75pu at 150% loading.

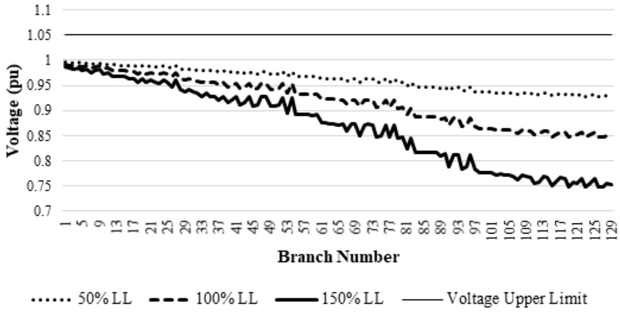

Figure 4: Bus Voltage with different loading for conventional optimization case

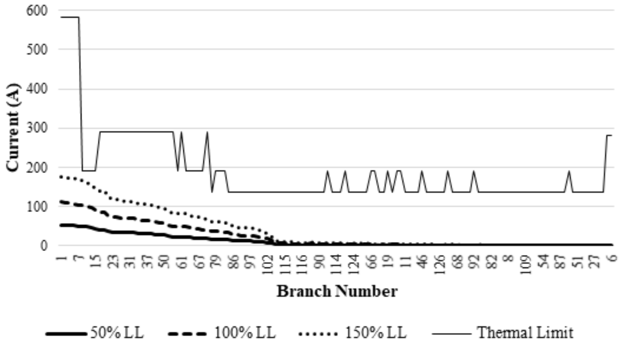

Figure 5: Branch Current with different loading for conventional optimization case

The loss at the 50%, 100% and 150% loadings are 34.73kW, 156.02kW and 409.78kW respectively.From Figure 5, it can be seen that all the line sections are within the limits.

3.3 Feeder Reinforcement Approach

With the conductor reinforcement using feeder selection, the changes need to be made to the existing feeder is tabulated in Table 2.

Table 2: Conductor selection with SSO

S. N.	Previous Conductor	New conductor	Length (km)
1	Weasel	Rabbit	4.224
2	Weasel	Dog	8.279
3	Rabbit	Dog	0.189
4	Rabbit	Dog-DC	9.490
5	Dog	Dog-DC	3.307

The loss at the 50%, 100% and 150% loadings are 26.94kW, 115.77kW and 282.88kW respectively. The voltage result in Figure 6 represents that the minimum feeder voltage is about 0.95pu ,0.9pu and 0.85pu

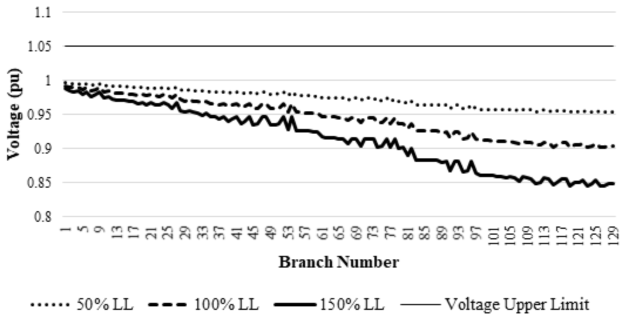

Figure 6: Bus Voltage with different loading for feeder reinforcement case

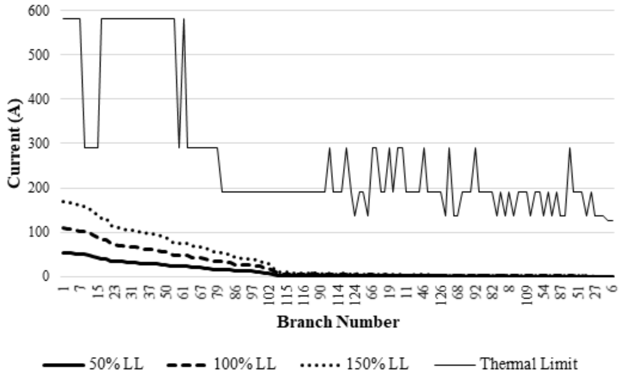

Figure 7: Branch Current with different loading for feeder reinforcement case

at 50%, 100% and 150% loading respectively. Also, it can be seen that all the line sections are within the limits in Figure 7.

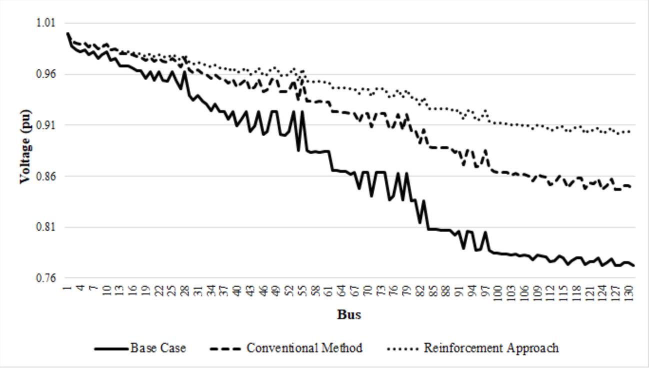

Figure 8: System voltage for base, conventional and reinforced cases

The voltage profile at 100% loading is compared for the different cases. From Figure 8 it is illustrated that the minimum system voltage for the system will be greater in the reinforced approach then conventional approach as compared to base case with values being 0.902pu, 0.847pu and 0.772pu respectively.

3.4 Optimum DG Location

With the injection of a Distributed Generation (DG), the hosting capacity needs to be evaluated for the feeder. The bus at ‘Kharka’ yielded the minimum loss at 100% line loading and generation at 100% of peak load, thus was considered as the optimum point for the injection. The hosting capacity was then evaluated with generation in range 25% - 200% of the peak feeder load.

3.5 Hosting Capacity

The hosting capacity of the feeder is calculated for the base, optimized and the reinforced case for the different loading levels and were evaluated considering both the voltage and the current limits. The graphs between maximum system voltage (vertical axis) and % generation (horizontal axis) in terms of load were plotted to determine voltage base HC whereas to determine current based HC the graphs between the minimum difference between the thermal limits and current flowing though each section was plotted in vertical axis.

Existing System

For the normal loading, when the generation exceeds about 55% of the peak load the voltage limits will be violated as in Figure 9. So, the hosting capacity of the system is about 55% considering the voltage limit.

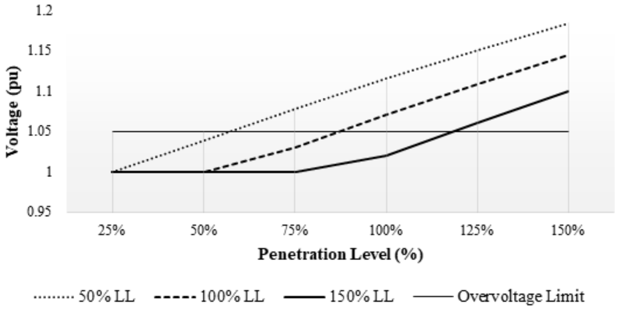

Figure 9: Voltage based HC under varying loads at base case

Considering the current limit, the generation can be made nearly at 180% of the peak load as shown in Figure 10. When the line is lightly loaded, the hosting capacity decreases as the voltage and the current limit gets easily violated.

So, in overall the generation can be made at about 55% i.e., 1.12MW for the existing base system so that both voltage and the current are within the limits.

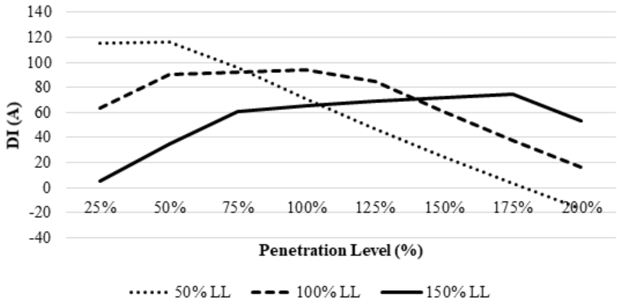

Figure 10: Current based HC under varying loads at base case

Conventional Optimization

When the line sections are optimized, the voltage-based hosting capacity of the system has increased as presented in the Figure 11. With the optimization of the conductor, the hosting capacity has increased to about 65% of the generation.

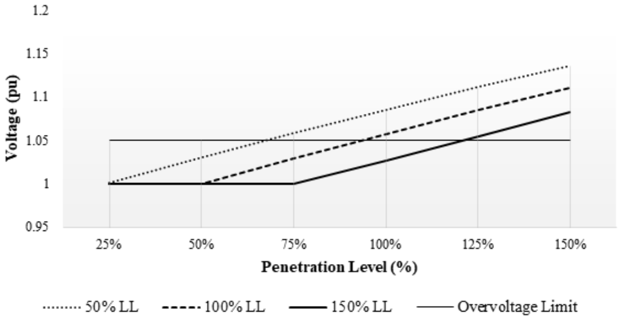

Figure 11: Voltage based HC under varying loads at conventional optimization case

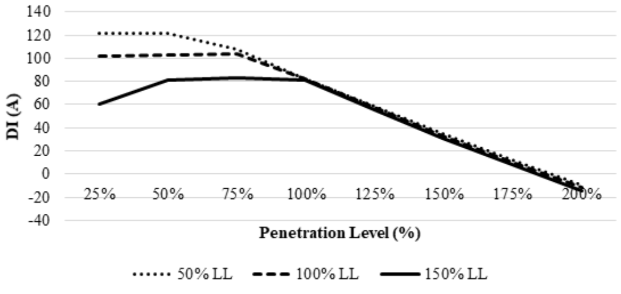

Figure 12: Current based HC under varying loads at conventional optimization case

The generation can be made at about 190% so that the current through each branch is within the limits as shown in Figure 12.So, the optimized system can withstand the generation of about 65% i.e., 1.32MW so that both the current and voltage limitations are not violated.

Feeder Reinforced Scenario

For the reinforced system using SSO, the hosting capacity is evaluated. It is evident from Figure 13 that the hosting capacity of the system has increased (to about 87% of the peak load), as compared to the base and the optimized scenario.

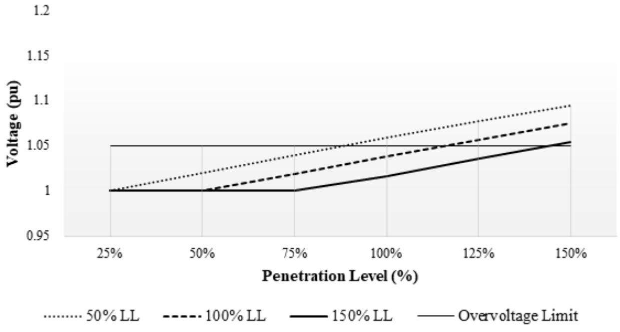

Figure 13: Voltage based HC under varying loads at feeder reinforcement case

Considering current at each branch, the generation can be made above 200% for the reinforced system. The minimum of the difference of the current carrying capacity and the current flowing through the section is almost identical for the different loading conditions as illustrated in Figure 14.

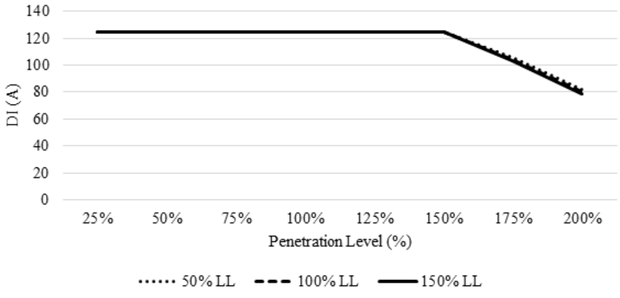

Figure 14: Current based HC under varying loads at feeder reinforcement case

So, considering both the current and the voltage limit, the generation can be made at about 87% of the current system peak i.e., 1.77 MW. The hosting capacity for the different cases can be compared in terms of MW as in Figure 15.

Since the radial length of the feeder was about 39km, with the placement of the generator also, the voltage limits were still below 0.95pu at 150% loadings with the feeder reinforcement. So, with the reinforced system integrated with DG at the optimum location, the voltage at the end section was found lower than the standards. So, the analysis was performed with injection of another DG too.

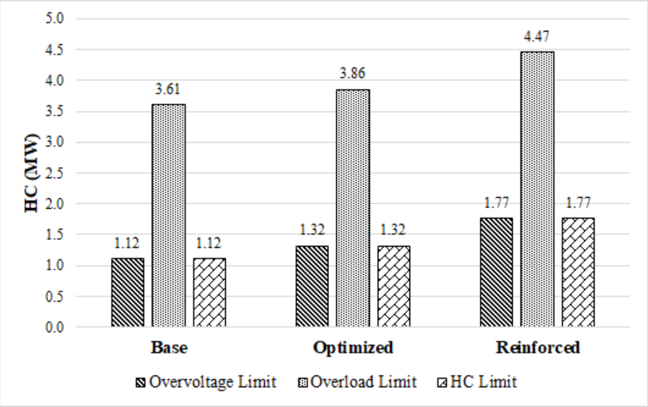

Figure 15: Hosting capacity of system at various cases considering voltage and current limits

3.6 HC with two DGs

Another optimum location for the generator was determined to be “Darbang Tallo” and the generators of remaining capacity 45%, 35% and 17.5% of 2.03MW load were considered for the base, optimized and the reinforced case respectively.

The hosting capacity for the existing, conventional optimization and feeder reinforcement case were evaluated to be less than 25% for each case i.e. the generation was to be made at less than 0.23MW, 0.17MW, 0.09MW. Also, this could not ensure the voltage to be within 0.95 pu at 150% loading for the selected system.

3.7 Financial Analysis

The financial analysis was considered with the inflation rate of 10%, and energy cost of Rs. 10. The BCR and IRR with conventional optimization and feeder reinforcement were 0.57, -5.59% and 1.30,3.32% respectively. With the payback period beyond 25 years and 17.24 years for the respective cases, the feeder reinforcement was more financial feasible than conventional optimization.

4. Conclusion

With the upgradation of conductor, the hosting capacity of the system was found to increase. In accordance with the loss results and hosting capacity, the feeder reinforcement approach is technically more effective than the conventional optimization further supported by the financial analysis.

For the Beni feeder, the feeder reinforcement with SSO would be the best alternative for immediate action.As, after some years, the voltage of the system would still be less than 0.95pu. So, a study can be made on placement of substation as future recommendations. Also, the effect on hosting capacity and financial feasibility can be studied for various types of DG.

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