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Optimal Placement of Solar PV with Transformer OLTC to Improve Voltage Profile in Distribution Feeder: A Case Study of Industrial II Feeder of Bharatpur DC

Pritam Raj Bista [a], Bhriguraj Bhattarai [b]

[a, b] *Department of Electrical Engineering, Pashchimanchal Campus, IOE, Tribhuvan University, Nepal*
Corresponding Email: [a] bista.pritam@gmail.com, [b] bhrigurajbhattarai@gmail.com

Abstract
This paper presents genetic algorithm (GA) optimization including cost optimization, power Loss minimization and voltage improvement to determine the optimal location and size of the Solar PV with substation transformer OLTC in distribution system. The proposed method minimizes the summation of difference of voltage at each bus from unity for improvement of voltage profile. The search method of GA is limited to 50 generations with 50 number of population, 0.8 crossover fraction and 0.01 mutation fraction. Load flow was carried out by using backward-forward sweep algorithm. MATLAB toolbox genetic algorithm function has been used for optimization coding. The optimized data has been simulated in electrical simulation software. The proposed procedure has been applied to IEEE 69 bus system and on a real distribution system, i.e. Industrial II feeder, Chitwan. The optimized result has been obtained according to different tap condition of OLTC. The financial analysis has been performed in Industrial II feeder as well. Result of this paper has been compared with previous publications and report. Simulation result shows that there is significant loss reduction and improvement of voltage profile and line loading after optimal placement of solar PV according to different tap conditions of OLTC in distribution system.

Keywords
Distribution System, Loss Minimization, Voltage Profile, Genetic Algorithm, Cost Optimization, OLTC, Solar PV

1. Introduction

Energy is the very essential requirement of the human life. The demand for power and energy is consistently increasing by an average annual rate of 4.83 % and the number of consumers has increased by 8 % in fiscal year 2019/20 [1].

Most of the rural 11 kV feeders in Nepal are radial type, lengthy in nature and some are overloaded too because of which, the problem of low voltage high loss is increasing. The low voltage problem of radial feeder can be solved by different methods as On-load tap changer (transformer), automatic power factor corrector (APFC), distributed generations (active/reactive power injection), upgrading and re-configuration of line.

Nowadays, substation transformers have the facility of changing tap to vary the voltage level during the load. This facility in some extent is useful to manage the low voltage problem. However, in long radial distribution feeder, it alone can't manage the voltage profile along the length within the acceptable range. In this paper, the optimization of DG with OLTC is proposed to solve this problem.

Gandomkar [2] decoupled and solved the tasks of optimal siting and optimal sizing separately. Ziari [3]had used an approximate time-varying multi-load level model with a hybrid optimization technique combining a discrete form of Particle Swarm Optimization and Genetic Algorithm operators. Parizad [4] used the Harmony Search heuristic algorithm to optimally site and size DG to reduce losses, improve voltage profile, improve system security and reduce Third Harmonic Distortion (THD). Kazemi [5] had proposed DG allocation for loss reduction and voltage improvement. Zadeh [6] proposed the Bacteria Foraging Algorithm (BFA) and Binary Genetic Algorithm (BGA) to investigate the optimal placement of DG with their comparison on IEEE 69-bus test systems. Te-Tien Ku [7] has studied the applications of OLTC with smart PV inverter integration for voltage profile improvement in distribution feeder. Mohamed [8] has introduced a hybrid Particle Swarm Optimization in addition to a Gravitational Search Algorithm (PSOGSA) and Moth Flame Optimization (MFO) and compared their results with other previous techniques. Nguyen [9] has presented the optimal voltage control of distribution networks based on modified particle swarm optimization.

The most common objective found in academic literature is voltage profile improvement, real power loss minimization, reliability and power quality improvement. However, this paper optimizes DG sizing and sitting to improve voltage profile according to different tap condition of OLTC.

The objective of this study is to analyze the optimal sizing and sitting of solar PV with OLTC on the basis of technical and financial aspects in the case of Industrial II Feeder of Bharatpur DC.

2. Methodology

The methodology followed in this study is summarized in flowchart in Figure 1. Necessary data of standard IEEE 69 bus and Industrial II feeder are obtained from literature review of published paper and Bharatpur 132/11 KV substation respectively. Matlab inbuilt function is used for Genetic algorithm for optimal allocation of Solar PV in the radial distribution system. Load flow study is required to determine the voltage, current and line loss. Algorithm mentioned in Figure 1 is used to obatin the optimum result.

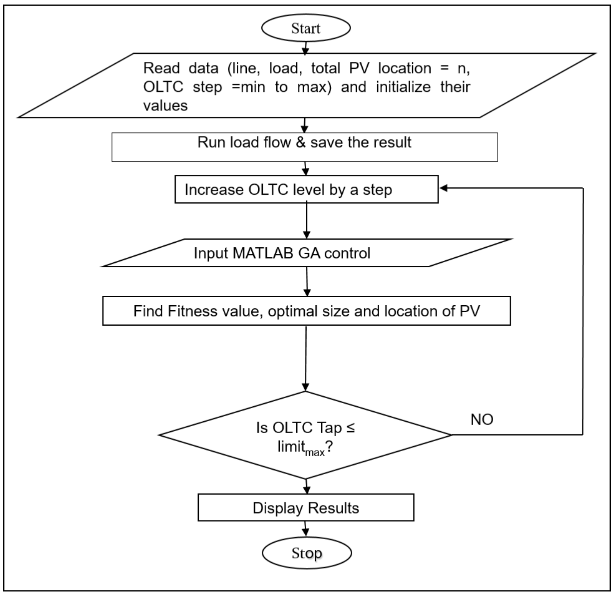

Figure 1: Flowchart to find optimal size and location of PV

2.1 Genetic Algorithm

In this research, Genetic Algorithm has been used for voltage profile improvement with consideration of optimal placement of the solar PV in distribution network. Stopping criteria determine the causes of the algorithm stopping. The search method of GA is limited to 50 generations with 50 numbers of population, 0.8 crossover fractions and 0.01 mutation fractions. The genetic algorithm has been implemented on MATLAB toolbox, i.e. a group of related functions. Each module of the algorithm has been implemented using a MATLAB function.

2.2 Problem Formulation

The objective function i.e. the fitness function of this study is to maximize voltage profile or minimize the voltage deviation as follows:

$$MinimizeV_{dev} = \sum_{y=1}^{n} (1 - V_y)^2 \tag{1}$$

Where, V_{dev} is the deviation of the voltage of each bus from 1 p.u. V_y is the p.u. voltage at y^{th} bus of N-bus distribution network.

Inequality Constraints are:

- $2 \leq PV Location \leq N$
- $Limit_{min}tap \leq OLTCstep \leq Limit_{max}tap$
- $PV penetration \leq 0.3 * Total size of the system$

2.3 Cost Optimization

Overall annual cost = Annualized capital costs - Annual energy cost saving due to reduction in line losses- Annual energy generation cost.

2.4 financial analysis of PV installation in industrial II feeder

Installation of PV will generate revenues with the energy cost associated with line losses and unit generation. And the overall capital cost of the PV system consists of the cost of PV system, the battery backup system and its installation and maintenance cost over its life time. In this paper, the capital cost of the solar PV system of 1 MWac with 500 kWh battery backup system is taken 120000 NPR/kW with VGF (Viability Gap Funding) required per kW as 61000 NPR/kW [10]. The simple payback period is calculated on the basis of the investment cost with respect to the revenue generation considering the following factor as; capacity Utilization factor (CUF) = 0.17 [10], operation and maintenance Cost = 1.5% of the capital cost [10] and solar PV PPA rate = 7.3 NPR/kWh [11].

2.5 Load Flow Analysis

Let us consider a branch of a radial distribution system as shown in the Figure 2, In the Figure 2,

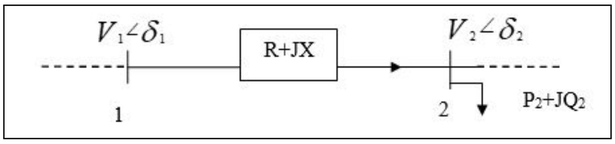

Figure 2: A branch of radial distribution network

1=Sending node of branch, 2=Receiving node of branch and P2+jQ2=Through Power at bus 2 and R+jX=Branch Impedance.Then, the voltage magnitude and phase angle at receiving end node can be written in generalized form,

$$V(m_2) = |B(j) - A(j)|^{\frac{1}{2}} \tag{2}$$

where,

$A(j) = P(m_2)R(j) + Q(m_2)X(j) - 0.5\,|V(m_1)|^2$

$B(j) = [A(j) - [R^2(j) + X^2(j)][P^2(m_2) + Q^2(m_2)]]^{\frac{1}{2}}$

and

$\delta(m_2) = \delta(m_1) - \tan^{-1}[\frac{P(m_2)X(j)-Q(m_2)R(j)}{P(m_2)R(j)+Q(m_2)X(j)+V^2(m_2)}]$

In above equations, j is the branch number, m_1, m_2 are sending end and receiving end node respectively.

Real power loss in the j^th branch is given by

$$PL(j) = \frac{R(j) * [P^2(m_2) + Q^2(m_2)]}{|V(m_2)|^2} \tag{3}$$

Reactive power loss in the j^th branch is given by

$$QL(j) = \frac{X(j) * [P^2(m_2) + Q^2(m_2)]}{|V(m_2)|^2} \tag{4}$$

Equations 3 and 4 are real and reactive power loss of the feeder. Load flow method to be used in MATLAB coding of this paper is backward-forward type.

If the deviation appeared in the voltage profile is less than the tolerance value, then load flow is said to be converged.

3. Case Study

3.1 IEEE 69 Bus System

It consists of 69-buses and 68 branches. The standard system of 69 bus has 12.66 kV and 10 MVA base value. The single line diagram of the system is illustrated in Figure 3. The total system rated load is of 3.801 MW and 2.694 MVAR.

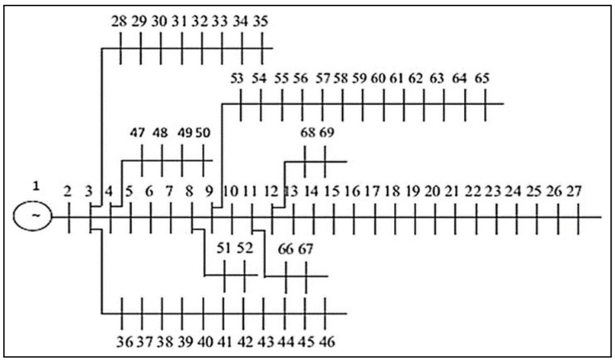

Figure 3: Single line diagram of IEEE-69 bus distribution system [8]

3.2 Industrial II Feeder

It covers most of the industrial area of Bharatpur Municipality. This feeder is 30 Km long with weasel/dog conductor and has 325/275 Amp maximum/average load [1]. The average load curve

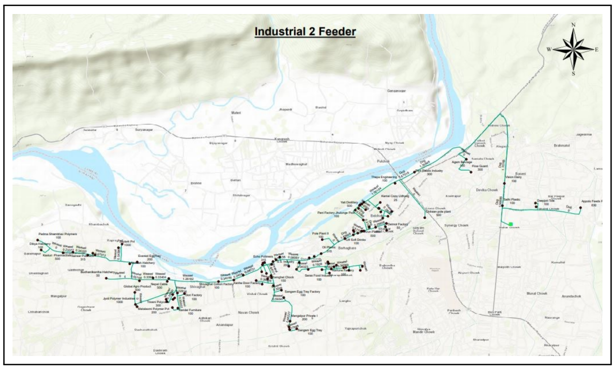

Figure 4: Single line diagram of Industrial II feeder

for a whole year has been drawn with the help of daily load curve at peaking day of separate 12 months as shown in 5. The average peak load of the Industrial II feeder in Year 2077 is 5002.44 kVA at 2 PM. This feeder contains 43 number of buses and 40 number of industries having one or more than one transformer for each industry with capacity 10200 kVA. Average load of Year 2077 on the basis of 12 peaking day of 12 months is taken as reference for load flow analysis

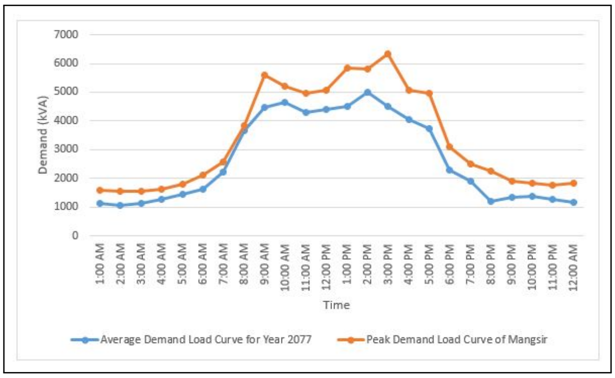

Figure 5: Demand Curve of Industrial II feeder

in this paper. From the load profile it is found that average maximum percentage loading in the feeder is 49 % of the total capacity of distribution transformer. So every distribution transformer is loaded to 49 % of its capacity and here after it is the 100% loading on the feeder and is considered as the base load for study in this paper. The average power factor of the feeder is found to be around 0.90. Total active and reactive power load is 4498.20 kW and 2178.58 kVAr respectively for load flow analysis.

4. Results and Discussion

The voltage profile and losses are observed before and after placement of solar PV in IEEE 69 bus test system and Industrial II feeder of Bharatpur DC as well. For that optimal size and the location of solar PV for voltage profile improvement were found by optimizing in MATLAB using Genetic Algorithm function of MATLAB toolbox. The various results were observed after modeling the optimized value obtained from MATLAB R2018b results in electrical simulation software as well. And executed on Intel Core i-5, 2.6 Giga Hertz (GHz) personal computer with 4 Giga Byte (GB) RAM.

4.1 Analysis of IEEE-69 bus system before PV placement

The summary of line loss and minimum voltage before placement of active power source (solar PV) in the feeder is shown in Table 1. From this table it was found that the algorithm used in MATLAB seems correct as comparison with the electrical simulation software. According to the result obtained from the MATLAB, there is up to 9.08 % voltage drop in the feeder. The least voltage was found on the bus number 65.

Table 1: Comparison of minimum voltage level and power loss before PV placement

Tools	Total Load	Minimum voltage (P.U.) /Bus No.	Power loss (kW)
MATLAB	3.801 MW,	0.9092(65)	224.94
Simulation	2.694 MVAR	0.9093(65)	223.70

4.2 Analysis of IEEE-69 bus system with OLTC before PV Placement

From the result, it was found that the voltage profile of IEEE-69 bus system is getting improved with the increment of tap from 1 to 1.05 P.U. The under voltage problem (i.e. below 0.95 P.U.) is mitigated along the line with the Tap changer above the 1.03 P.U.

4.3 Optimal placement of PV in IEEE-69 bus distribution system without OLTC

The voltage profile of the standard test feeder after placement of active power source is presented in Figure 6. The voltage profile of feeder was found to be improved for all PV placement cases. And it was found that overall voltage profile is better for 2 PV placement case. However, the difference in improvement for 2 PV placement case is not higher with comparison to rest. The improvement in voltage of minimum voltage node for 2 PV placement case was only 0.24% and 0.12% more than 1 and 3 PV placement cases respectively.

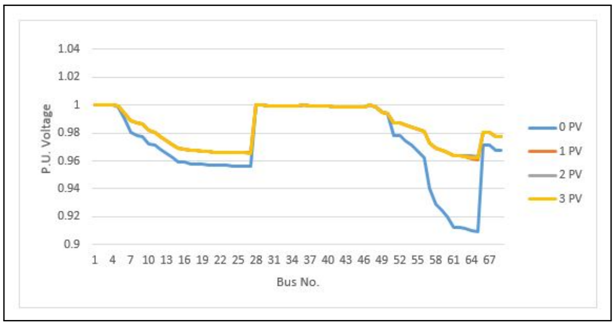

Figure 6: Voltage profile of IEEE-69 bus system with the placement of solar PV

4.4 Optimal placement of PV with OLTC in IEEE-69 bus distribution system

From the optimization result, voltages at minimum voltage node are obtained for all PV placement cases and are presented in Figure 7.Maximum improvement in minimum voltages was obtained for 3 PV placement cases with tap changer at 1.02, 1.03, 1.04 and 1.05 and for 2 PV placement cases with the tap changer at 1 and 1.01. From the results, at tap changer

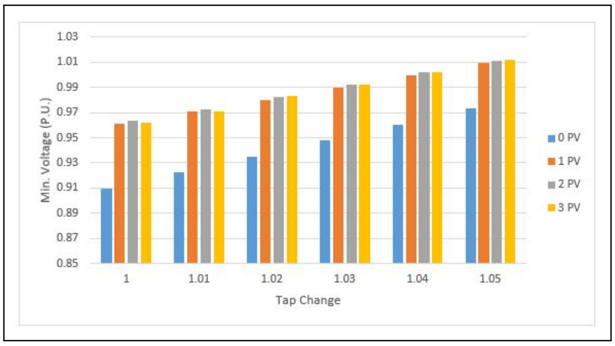

Figure 7: Voltage at minimum voltage node in IEEE-69 bus system

1, 1.02 and 1.03, it was found that there were minimum losses for 3 PV placement cases. The reduction in active power loss at tap changer 1, 1.02 and 1.03 were 72.88%, 72.50% and 72.41% respectively from initial case without PV placement. Similarly, at tap changer 1.01, 1.04 and 1.05, it was found that there was minimum loss for 2 PV placement cases. The reduction in active power loss at tap changer 1.01, 1.04 and 1.05 were 72.56%, 71.94% and 72.20% from initial case without PV placement. And the minimum size of solar PV placement, i.e. 0.923 MW, was found for 3 PV placement case for tap changer at 1.05. The difference in total size of solar PV between maximum size (3 PV placement case with tap changer at 1) and minimum size (3 PV placement case with tap changer at 1.05) is just around 0.199 MW.

Upon analyzing the optimization of PV location and sizing with different OLTC tap changer, maximum improvement in voltage at minimum voltage node was found to be 10.14% for 3 PV placement of size 0.92388 MW with OLTC tap changer at 1.05 (maximum tap) with the active loss reduction of 71.55%. The voltage at minimum voltage node nearest to 1 P.U. in the feeder was found to be 0.999604 P.U. for 1 PV placements with size 0.96804 MW with OLTC tap changer at 1.04 tap with the active loss reduction of 71.94%.

4.5 Analysis of Industrial II feeder before PV placement

The voltage profile obtained on various loading conditions is as shown in Figure 8. And minimum voltage, minimum voltage bus number and losses at various loading conditions are as shown in Table 2.

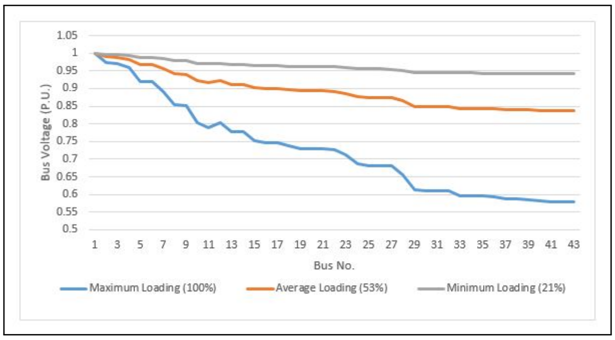

Figure 8: Voltage Profile of Industrial II at different loading condition

Table 2: Summary of load flow at various loading in industrial II feeder

Loading Case	Minimum Voltage (p.u.) /Bus No.	Active power loss (MW)	Base load (MW)
Maximum (100%)	0.578(43)	1.846	4.50 MW
Average (53%)	0.837(43)	0.281	
Minimum (21%)	0.918(43)	0.036	

From above voltage profile curve and table, it was found that there is up to 42 % voltage drop in the feeder on maximum load condition i.e. 100% loading. Drop in voltage reduces on reducing the loading of the line. The least voltage was found on bus number 43 which is the farthest bus of the feeder from supply point. During average loading, 47% reduction on loading has resulted 85% reduction in active power loss and 45% increase in voltage. The technical line loss of the system was found to be 10.54% at that condition. In next, all the analysis of this industrial II feeder was done on the basis of average loading condition of yearly average demand load curve.

4.6 Analysis of Industrial II system with OLTC before PV Placement

The voltage profiles of the Industrial II feeder with the different tap condition i.e. 1, 1.01, 1.02, 1.03, 1.04 and 1.05 are as shown in Figure 9. The voltage profile of Industrial II feeder is getting improved with the increment of tap changer from 1 to 1.05 P.U. The under voltage problem is getting reduced along the line with the increment of tap changer.

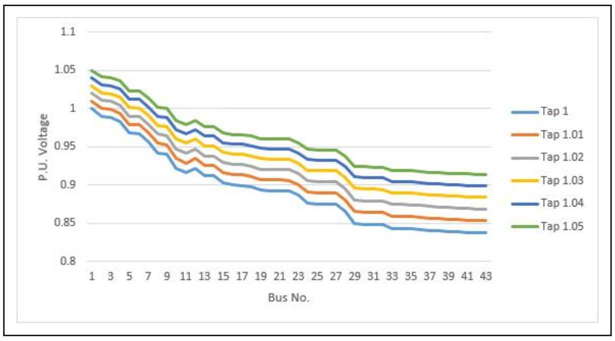

Figure 9: Voltage profile of Industrial II feeder with OLTC

4.7 Optimal placement of PV in Industrial II feeder without OLTC

The voltage profile of the Industrial II feeder after placement of active power source is presented in Figure 10. The voltage profile of feeder was found to be improved for all PV placement cases. And it was found that overall voltage profile is better for 3 no. of PV placement case. However, the difference in improvement for 3 no. of PV placement case is not higher with comparison to rest. The improvement in voltage of minimum voltage node for 3 PV placement case was only 0.13% and 1.31% more than 2 PV and 1 PV placement cases respectively.

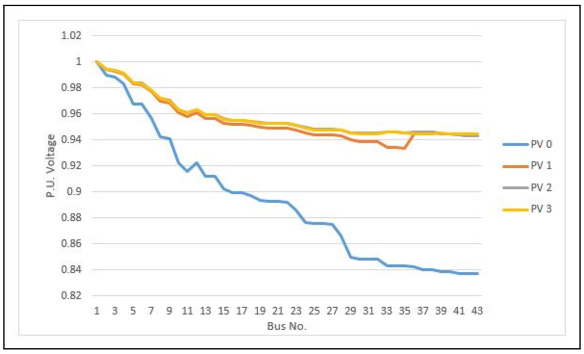

Figure 10: Voltage profile of Industrial II feeder with PV placement

4.8 Optimal placement of PV with OLTC in Industrial II feeder

A typical convergence graph of GA optimization obtained in MATLAB is as shown in Figure 11. From the optimization result, voltages at minimum voltage node are obtained for all PV placement cases and are presented in Figure 12. In the optimized result, maximum improvement in minimum voltages was obtained for 3 no. of PV placement cases with all tap changer.

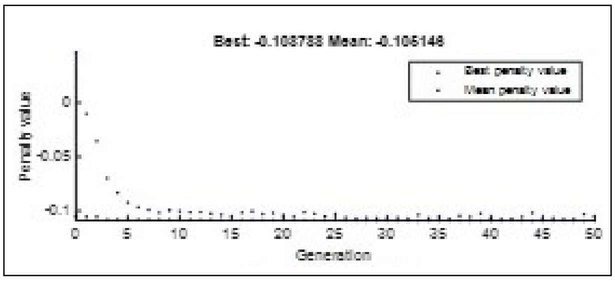

Figure 11: Screen shot of generation graph of GA in MATLAB

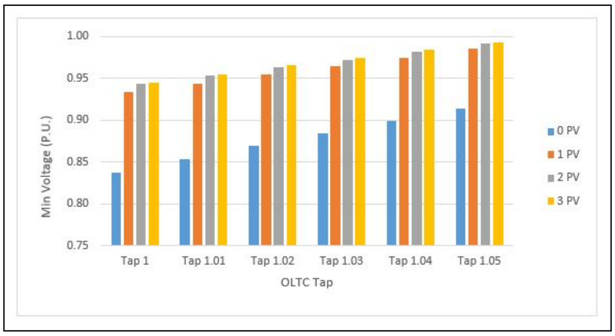

Figure 12: Voltage at minimum voltage node in Industrial II feeder

The comparison of loss and total size of solar PV for each case are as shown in Figure 13 and Figure 14 respectively.

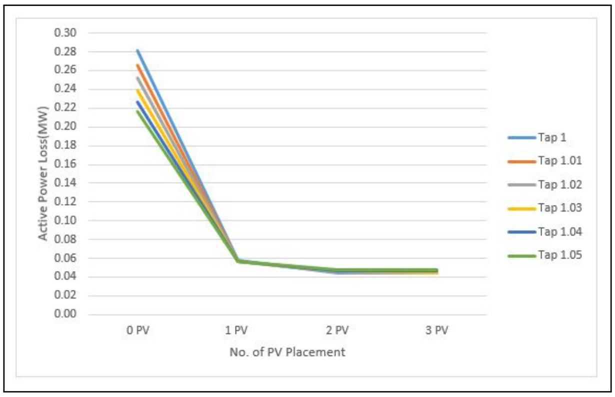

Figure 13: Loss of the Industrial II feeder with PV placement and OLTC

At all tap changer condition, it was found that there were minimum losses for 3 PV placement cases. The reduction in active power loss at tap changer 1, 1.01, 1.02, 1.03, 1.04 and 1.05 were 84.17%, 84.19%, 84.37%, 84.11%, 83.46% and 83.09% respectively from initial case without PV placement.

The minimum size of solar PV placement was found to be 0.821 MW for 1 PV for tap at 1.05. The difference in total size of solar PV between maximum size (2

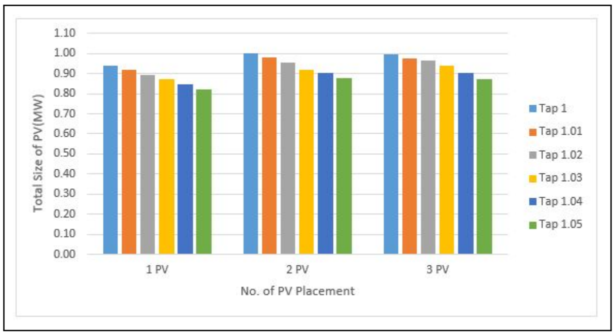

Figure 14: Total size of PV with the number of PV placement for Industrial II feeder

PV placement with tap at 1) and minimum size (1 PV placement with tap at 1.05) is just around 0.182 MW.

Upon analyzing the optimization result of PV location and sizing with different OLTC tap changer, maximum improvement in voltage at minimum voltage node was found to be 18.61% for 3 PV placement of size 0.874 MW with OLTC tap changer at 1.05 (maximum tap) with the active loss reduction of 83.09%.

4.9 Line loading and short circuit level in Industrial II feeder

The loading on the line and short circuit level of industrial II feeder before and after PV placement are shown in Figure 15 and Table 3 respectively. Figure 15 shows that the loading of the line was found to be improved with the integration of the solar PV in the feeder. Table 3 shows that the fault current did not increase significantly after placing the PV and hence no need to modify protection system.

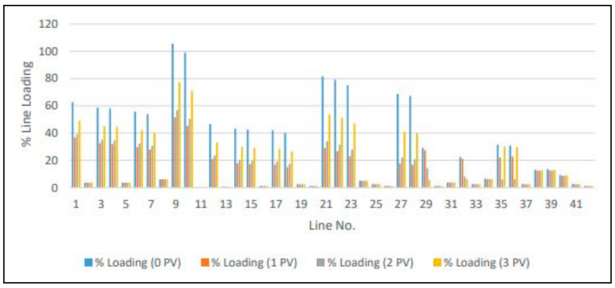

Figure 15: Line Loading of Industrial II feeder before and after PV placement

Table 3: Short circuit current at 3 phase fault before and after PV placement

Faulted Bus	I"(kA)			
	without PV	with 1PV	with 2PV	with 3 PV
43	0.794	0.841	0.865	0.942

4.10 Comparison of results with published paper

The result from [6, 8, 10] are used to compare and verify the result of this paper as shown in Table 4.

Table 4: Comparison of results with published papers and report

Result on IEEE 69 bus	[6]	[8]	[10]	This Paper
Loss without DG (kW)	225	224.98	-	224.94
Minimum voltage bus without DG	-	65	-	65
Minimum voltage without DG (P.U.)	-	0.9091	-	0.9091
Optimal location/ size(1DG)(MW)	1.892 (61)	-	-	1.117 (61)
Optimal location/ size(2DG)(MW)	2.803 (61, 12)	-	-	1.115 (61, 64)
Optimal location/ size(3DG)(MW)	-	2.997 (21,62 ,64)	-	1.123 (61,64 ,65)
Loss with 1 DG (kW)	26	-	-	62.19
Loss with 2 DG (kW)	15.5	-	-	61.46
Loss with 3 DG (kW)	-	89	-	61
Reduction in losses 1 DG(%)	88.4	-	-	72.35
Reduction in losses 2 DG(%)	93.2	-	-	72.68
Reduction in losses 3 DG(%)	-	60.44	-	72.88
Minimum bus voltage 3 DG (P.U.)	-	0.994 (57)	-	0.963 (65)
Payback period at PPA rate 6.98 NPR/kWh	-	-	22	21
Payback period with considering line loss at PPA rate 7.3 NPR/kWh	-	-	-	16

The results are quite similar without placement of DG. The optimal values obtained after placement of DG were different due to the cost optimization parameter used in GA and the DG penetration level restriction (i.e.30% of load) used in this paper. However, the optimal values obtained without cost optimization and penetration level restriction were quite similar to the published papers.

The revenue generation in this paper is higher than [10] due to the extra revenue generation from loss reduction in the distribution line and the higher PPA rate as well. Hence, the overall payback period is around 6 years less than the payback period of 22 years mentioned in report [10]. Investment would by financially worthy if the capital cost of PV reduces further upon development of PV market.

5. Conclusion

This paper presents the methodology for the optimal siting and sizing of solar PV according to OLTC in radial distribution system using Genetic Algorithm with cost optimization. After optimal placement of solar PV with OLTC, for IEEE 69 bus system, the voltage at minimum voltage node near to 1 P.U. was found to be 0.9960 P.U. with 1 PV placement of size 0.968 MW (61) at tap changer 1.04. And the maximum active power reduction was found to be 72.88% with 3 PV placements of total size 1.123 MW (61,64,65) at tap changer 1. Similarly, Minimum total PV size was found to be 0.92388 MW (61,64,65) for 3 PV placement case at tap changer 1.05. Similarly, for Industrial II feeder, the voltage at minimum voltage node near to 1 P.U. was found to be 0.993 P.U. with 3 PV placements of total size 0.874 MW (33,39,41) at tap changer 1.05. And the maximum active power reduction was found to be 84.37% with 3 PV placements of total size 0.964 MW (33,39,41) at tap changer 1.02. Similarly, Minimum total PV size was found to be 0.821 MW (37) for 1 PV placement case at tap changer 1.05. Overall, the simple payback period of the investment on the solar PV with battery backup system in industrial II feeder to improve voltage profile and reduce line loss was found to be around 16 years.

Thus, it can be concluded that, Genetic Algorithm with cost optimization can be used to find the optimal size and location of solar PV according to OLTC for voltage profile improvement of the feeder and with the placement of solar PV in the feeder, voltage profile, line loading and loss reduction of the feeder has been improved. However, no significance difference in improvement was obtained with increment of solar PV placement number. The better voltage profile and optimized smaller PV size has been obtained in higher tap level of OLTC and maximum reduction in power loss has been observed in optimized higher PV size in lower tap level of OLTC. The short circuit level of the system did not increase significantly after placing the PV and hence no need to modify protection system.

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