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Maximum Permissible Level of Wind and Solar Based DG Penetration in Sub-Transmission System without Violating the Techno-Economic Benefits

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Abstract:
The electric utilities are facing challenging issues such as quality, reliability of power supply, voltage stability, power loss, and economic concerns. This is due to risingelectrical energy needs and utilization of Distributed Energy Resources (DERs) into the modern power system. DERs include solar Photo Voltaic (PV) system, small wind generators, battery energy storage systems, etc. These elements had added new complexity in the design and performance of the distribution system. In this paper, the maximum permissible limit of wind and solar-based Distribution Generation units(DGs) injection on the sub-transmission systemwaspredicted without violation of the technical and economic aspects.The objective is to mitigate the power loss (Ploss) and enhance the voltage profile (VP) considering net economical cost-benefit to the distribution utility. The IEEE 14-bus sub-transmission system was utilized for the study purpose. The results illustrate the maximum permissible limit of wind and solar-based DG penetration on the test system is 40% and 75% respectively in terms of technical aspects. Similarly, the permissible level of economical cost-benefit is 100% for solar-based DG and 55% for wind-based DG. Comparing solar and wind-based DG injection into the test system, solar-based DG contributed positively to the test system with techno-economic benefits.

Keywords: *Sub-transmission system, Distributed Generation,Wind and Solar, Techno-Economic Benefit, DG Penetration Level..*

I. INTRODUCTION

In the future power system, the role of DGtechnologies will gain more importance due to the increasing demand in electrical energy. DG is a small scale electrical power source connected directly at the distribution side or on the customer load points. DG technologies include wind turbines, biomass, PV, fuel cells, geothermal, microturbines, etc. Optimal deployments of DG into the electrical networks have positive benefits to the system. Significant benefits such as reduce power losses, improve VP, enhance stability, power quality, reliability, etc[1]. Optimal deployment of DG in the system plays a crucial role in achieving the positive benefits to the system. High penetration of DG into the electrical network may adversely affect the positive benefits of the system. Therefore, it is important to predict the limit at which DG penetration is beneficial to the system.

Many authors had employed various methods of optimization for optimal deployment of DG into electrical networks. The optimization methods are classified into three categories, such as conventional, meta-heuristic and hybrid method based optimization. The objective function for the DG optimization problem may be considered technical, economical and environmental aspects. Table I, illustrate about few researchers work on the DG optimization problem in the electrical system using various optimization techniques, objective functions, and the test system considered.

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Table I: Literature review of DG optimization problem

Authors	Optimization method	Objective function	Comments (Test system)
D. Q. Hung et al. [2]	Analytical	Real power loss reduction	Single objective (RDS)
A.A. Abou El-Elaet. al. [3]	Genetic algorithm	Reduce P_{loss} and improve VP	Only technical objective functions (RDS and mesh system)
D.B. Prakash et. al. [4]	Particle Swarm Optimization	Reduce P_{loss} and improve VP	Only technical objective functions (RDS)
BanajaMohanty et. al. [5]	Teaching Learning Based Optimization	Reduce P_{loss}, improve VP and Voltage Stability Index	Technical objective functions (RDS)
Kyu- Ho Kim et. al. [6]	Fuzzy-GA	Minimize the power lost the cost	The economical objective function (RDS)
A.S.O. Ogunjuyigbe et. al. [7]	-------	Reduce P_{loss} and improve VP	Technical issues of DG units injection (Sub transmission system)

From Table I, it is found that many researchers choose objective as P_{loss} minimization and enhancement of VP for DG optimization problem in RDS. Few authors have worked on both technical and economic issues as the objective of placing the DG optimization problem. In this paper, the techno-economic benefitofType-2 DG units (PV) and Type-4DG units (Wind) placement on the sub-transmission system at different penetration levels (PLs) had been analyzed. In this study, the IEEE 14-bus sub-transmission system is employed as the test system.

II. Classification of DG Technologies

DG units are marked as different based on their output power characteristics. They are classified into four types as follows:

- Type 1: Injects both active and reactive power. Example: Small hydro, Geothermal.
- Type 2: Injects active power only. Example: PV, micro turbines, fuel cells.
- Type 3: Injects only reactive power. Example: Synchronous compensators
- Type 4: It consumes reactive power and injects active power. Example: Wind turbine

III. Problem Formulation

The basic objective functions considered for optimal deployment of DG in the sub-transmission system is to mitigate the electrical P_{loss} and to enhance the VP. The technical and economic profit (net cost-saving) impact of placing DG is considered in this study.

A. Real Power loss (RPL) and Reactive power loss (QPL)

Minimization of electrical power losses (i.e., RPL and QPL) is the major objective considered for the injection of DG into the electrical system. They are mathematically evaluated as follows [7].

i. Real power loss:

$$\text{Minimize RPL} = \sum_{i=1}^{n} (I_i^2) \times r_i \quad (1)$$

ii. Reactive power loss:

$$\text{Minimize QPL} = \sum_{i=1}^{n} (I_i^2) \times x_i \quad (2)$$

B. Voltage Profile (VP)

VP is the last objective function considered in this paper. It is evaluated as follows [5]:

$$\text{Minimize VP} = \sum_{\mathbf{k=1}}^{\mathbf{N}} (\mathbf{V_k} - \mathbf{V_{rated}})^{\mathbf{2}} \quad (3)$$

where,

n The number of lines.

$\mathbf{r_i}$&$\mathbf{x_i}$ Resistance and reactance of the i^{th} line respectively.

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$\mathbf{I_i}$	Line current.
N	The number of buses.
$\mathbf{V_k}$	The voltage at k^{th} bus.

C. Multi-Objective Index (MOI)

The objective is to minimize the weighted MOI, it is given by,

$$\text{Min. } f = \lambda_1{*}RPL+\lambda_2{*}QPL+\lambda_3{*}VP \quad (4)$$

and $\sum_{i=1}^{3}\lambda_i = 1.0 \quad \forall\ w_i \in [0,1]$ (5)

where λ represent weightage factor. In this paper,

Table II shows the assigned value for the corresponding objective functions.

Table II. Weightage factors for RPI, QPL and VP

Obj. fun.	RPI	QPL	VP
λ	0.5	0.2	0.3

D. Penetration Level(PL) of DG

It is the amount of active power that the DG can supply to the network. It is evaluatedby [5],

$$\%\,\mathbf{PL} = \frac{P_{DG}}{P_{load}} \times 100\% \quad (6)$$

where,

$\mathbf{P_{DG}}$	Active power supplied by the DG.
$\mathbf{P_{load}}$	Network active power demand.

E. Constraints

i. Voltage limits:

$$|\mathbf{V_{min}}| \le |\mathbf{V_i}| \le |\mathbf{V_{max}}|$$

ii. DG size limit:

$$\mathbf{P_{DGn}^{min}} \le \mathbf{P_{DGn}} \le \mathbf{P_{DGn}^{max}},\ \ \forall_{n,}\ \mathbf{n} = \{1,2,3,\ldots,\mathbf{N}\}$$

where $\mathbf{P_{DGn}^{min}}\&\mathbf{P_{DGn}^{max}}$ are the min.& max. active power injected by DG respectively.

iii. DG Penetration level constraints

$$\mathbf{10\%\ of\ P_{load}} \le \mathbf{P_{load}} \le \mathbf{95\ \%\ of\ P_{load}}$$

IV. ECONOMIC ASPECTS OF DG INTEGRATION

The DG investment cost (DG_I) is evaluated as given below [8].

$$\mathbf{DG_I} = \sum_{i=1}^{dgn} \mathbf{K_{I,DG}\,P_{DG\,(rated),i}} \quad (7)$$

The operation and maintenance cost of the DG (DG_{OM}) is evaluated as given below:

$$DG_{OM} = \sum_{i=1}^{dgn} P_{DG,i}\,.K_{OM,DG}.T \times \sum_{y=1}^{nyr}\left(\frac{1+InfR}{1+IntR}\right)^{y} \quad (8)$$

where,

$K_{I,DG}$	DG investment cost.
$P_{DG,i}$	Active power supplied by the DG at i^{th} bus.
dgn	The number of DG units.
$K_{OM,DG}$	DG_{OM}cost.
T	Duration Time.
nyr	No. of years.
InfR	Inflation rate
IntR	Interest rate

The total equivalent annual cost of DG (DG_{AEC}) is written by eq.9.

$$\mathbf{DG_{AEC}} = \mathbf{DG_I} + \mathbf{DG_{OM}} \quad (9)$$

The cost of power purchased (C_P)by the utilities is given by,

$$C_P = \Delta P_p.K_p.T \times \sum_{y=1}^{nyr}\left(\frac{1+InfR}{1+IntR}\right)^{y} \quad (10)$$

$$\Delta P_p = P_{(p,\ before\ DG)} - P_{(p,\ after\ DG)} \quad (11)$$

where,

ΔP_p	Reduction in real power purchased.
K_p	Market energy price ($/MWh).

The net economic profit due to injection of DG is given by,

$$\text{Net profit (\$)} = C_P - DG_{AEC} \quad (12)$$

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V. Simulation Results and Discussion

For the test system shown in Fig. 1, the sum of active and reactive power load is259 MW and 73.5 MVAR respectively. The real and reactive power losses obtained by the Newton Raphson load flow method are 13.59 MW and 56.91 MVAR respectively. The estimated parameters cost for calculating DG cost analysis are tabulated in Table III.

Table. III. DG cost specifications

Parameter	Value
$K_{I,DG}$ (\$ / MW)	318000
$K_{OM,DG}$ (\$ / MWh)	36
Planning period	5
InfR %	9
IntR %	12.5
K_p (\$ / MWh)	49

In the power system, PV and PQ buses are considered as generator and load buses respectively. In this paper, the different types of DGs units are allocated at PQ buses of the test system considered for study purposes. The DG units are placed at the PQ buses for better performance of the system.The amount of reactive power consumed byType-4 DG is simply calculated by the equation given below [9].

$$Q_{DG,i\,(consumed)} = 0.05 + 0.04\,P_{DG,i}^2 \quad (13)$$

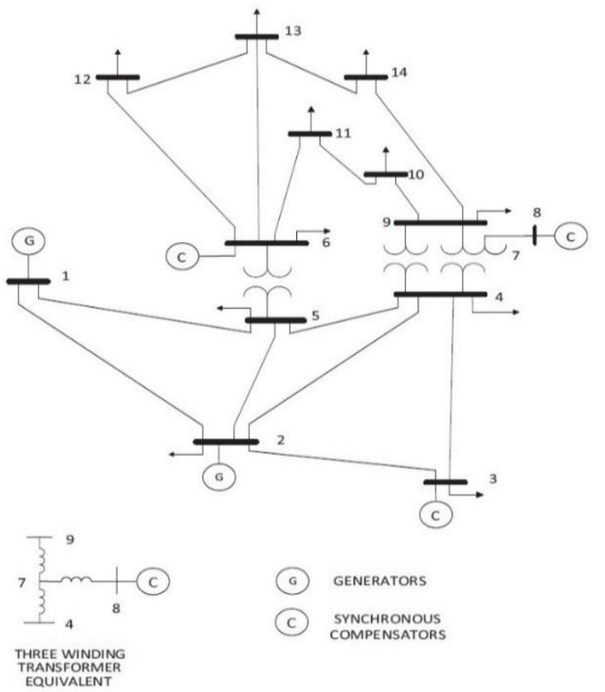

Fig. 1. IEEE 14-bus sub-transmission network

Table IV. Techno-economic impact with an increase inPL of Type 2 DG unit

PL%	RPL	QPL	IMO	Net Saving (Million \$)
10	10.72	43.12	0.8767	27.17
15	9.04	38.11	0.7938	41.46
20	8.09	33.71	0.7393	53.25
25	7.01	29.15	0.6892	65.49
30	5.98	26.01	0.6466	77.53
35	5.40	21.38	0.6260	87.87
40	4.41	18.34	0.5731	99.76
45	3.74	16.28	0.5362	110.95
50	3.17	12.95	0.526	121.01
55	2.74	11.14	0.5089	130.91
60	2.41	9.76	0.4964	140.7
65	2.09	8.40	0.4962	149.91
70	1.95	7.85	0.4932	158.75
75	1.91	7.71	0.4950	167.2
80	1.97	8.00	0.5017	175.33
85	2.04	8.30	0.5232	183.41
90	2.28	9.36	0.5387	190.87
95	2.58	10.61	0.4966	198.12

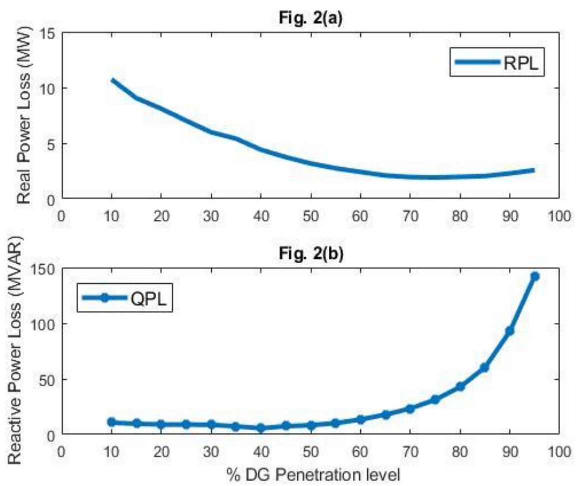

Fig. 2 (a-b). Characteristics of RPL and QPL for Type-2 DG with an increase in PL

Table V. Techno-economic impact with an increase inPL of Type 4 DG unit

PL%	RPL	QPL	IMO	Net Saving (Million \$)
10	10.64	44.25	0.7969	27.34
15	9.61	39.47	0.6677	39.39
20	8.97	36.48	0.5831	50.05

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25	8.96	33.79	0.5716	58.42
30	8.66	35.46	0.5863	59.51
35	7.40	35.95	0.5910	80.72
40	5.58	29.55	0.4712	95.64
45	7.47	47.00	0.9151	97.14
50	8.37	60.35	1.2397	102.2
55	10.14	83.03	1.7784	104.08
60	13.53	63.815	1.1669	100.15
65	17.833	81.63	1.55	92.89
70	23.34	103.62	2.033	81.27
75	31.19	134.63	2.703	61.16
80	42.63	179.38	3.6719	28.03
85	60.27	247.94	5.1623	-27.54
90	92.72	373.35	7.9045	-136.7
95	142.49	565	12.1179	-312.62

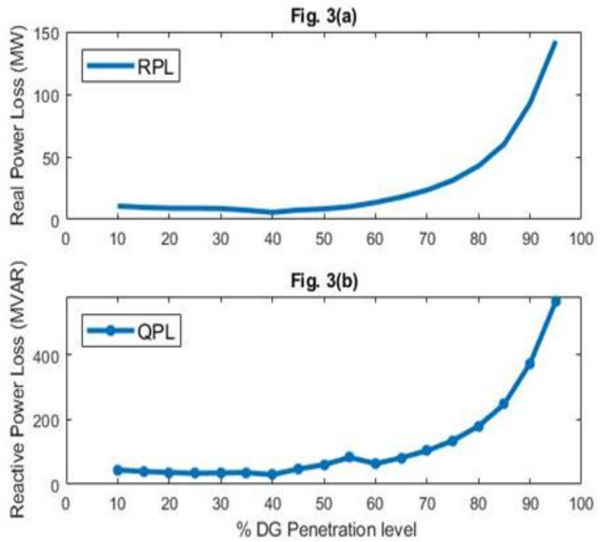

Fig. 3 (a-b). Characteristics of RPL and QPL for Type-4 DG with an increase in PL

The simulation results of the technical and economic impact with growth in PL of Type-2 DG on the IEEE 14-bus test system are shown in Table IV. From Fig. 2(a-b), it is observed that the Type-2 DG penetration level is technical beneficial up to 75%. Similarly, Table V shows the results obtained for technical and economic impact with the rise in PL of Type-4 DG units. From Fig. 3(a-b), it is clearly shown that the Type-4 DG PL is technical beneficial up to 40%. The net economic saving in cost due to an increase in DG location on IEEE 14-bus test system is beneficial up to 100% and 55% for Type-2 DG and Type-4 DG units respectively. The graphical representation of it is shown in Fig. 4.

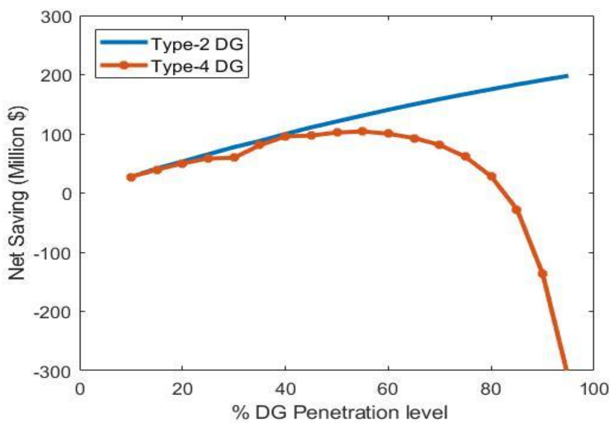

Fig. 4.Graph of net economical benefit with growth in PL of DG

VI. CONCLUSION

In this paper, the techno-economic impact due to the rise in PL of DG had been analyzed on a sub-transmission system. Type-2 DG units (which injects only active power into the system) and Type-4 DG units (which injects active power and consume reactive power into the system) are considered for study purposes. Technical issues in the DG optimization problem include a reduction in real and reactive power losses and enhancement of VP in the system. IEEE 14-bus test system is considered for the test system. The simulation results showed that at the initial penetration level, DG injection at an optimal location had contributed positively to the system with reduced power losses and economically beneficial. However, as the PL increased, the power losses began to rise. The maximum penetration of Type-2 DG and Type-4 DG units into the test system in terms of technical aspect is 75% and 40% respectively. Similarly, for economical aspect, it is beneficial up to 100% and 55% PL for Type-2 DG and Type-4 DG units respectively. The obtained results showed that the with Type-2 DG units' injection (PV system), good performance can be obtained compared to Type-4 DG units (Wind turbine) injection into the system.

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