Analysis of Impact of Electric Vehicle Charging Station on Voltage Stability Issues and Improvement Using Distributed Generation (DG)

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Abstract
Electric vehicles (EVs) are increasingly viewed as a pivotal component in the global transition towards sustainable transportation. In India, although EV adoption is currently modest compared to conventional vehicles, there is a widespread expectation that the penetration of EVs will undergo a substantial increase in near future. This anticipated growth is driven by the recognition of the environmental and socio-economic benefits of reducing reliance on fossil fuels, fostering a significant market for EVs. However, the increasing adoption of EVs has significant implications for power grids and distribution networks due to the substantial power demand required for recharging EV batteries. The integration of numerous EV charging stations (EVCS) into the utility grid generates harmonics, complicating the voltage profile and impacting overall voltage stability. This research paper provides an in-depth analysis of the influence of electric vehicle charging stations in India on voltage stability and voltage profile. The paper aims to contribute valuable insights into the evolving landscape of electric vehicle integration with the stability and quality of power systems in evolving energy infrastructure.

Keywords: Electric Vehicle Charging Station, Harmonics, Power Grid, Voltage Profile, Voltage Stability

INTRODUCTION

The concept of Electric Vehicles (EVs) is relatively novel in the transportation sector, gaining significant attention due to its numerous advantages such as reduced environmental pollution, cost-effectiveness, and decreased reliance on petroleum. The global market encompasses three primary types of electric vehicles: Plug-in Hybrid Electric Vehicles (PHEVs), Hybrid Electric Vehicles (HEVs), and Battery Electric Vehicles (BEVs) [1].

In India, the adoption of EVs like Easy bikes, auto-rickshaws, and electric bikes has been rapidly increasing, constituting more than 7% of the total registered vehicles as of March 2023.

These vehicles operate using electric motors powered by batteries, contributing to the shift towards a more sustainable and eco-friendly transportation system [2]. However, the surge in EV usage has presented challenges, with the demand for electricity exceeding 450 MW daily in India, leading to strain on the existing power infrastructure. Charging EVs requires substantial power and time, exacerbating the strain on the system. Moreover, the insufficient availability of charging stations prompts EV owners to

resort to illegal residential connections, causing system losses in the power sector.
To facilitate the further penetration of EVs, there is a critical need to establish an sample number of charging stations strategically located at various points [3]. EV batteries can operate on either a single-phase or three-phase supply system. While single-phase supply points are more widely available, three-phase systems offer higher power and faster charging capabilities. However, the power electronic converters used in EV chargers, akin to non-linear loads, introduce harmonics into the current, affecting the voltage profile of the power network.
The non-linear loading characteristic of EV chargers can lead to distorted voltage waveforms and nonlinear voltage drops, impacting the performance of distribution transformers. This influence manifests through increased power losses in transformer windings, diminishing power output.
This research paper utilizes MATLAB programs to comprehensively analyze the impact of EVs on the Voltage Profile and Voltage Stability on power distribution network in India.
In summary, the transition to electric vehicles presents a multifaceted landscape of benefits and challenges, necessitating careful consideration and strategic interventions to ensure a sustainable and harmonious integration into existing transportation and power systems. The complexity of this paradigm shift requires continued research and innovative solutions for a successful and environmentally conscious future [4].

EV CHARGER INFORMATION

In the context of Electric Vehicle (EV) chargers, operating as non-linear loads, their main impact on the power system in India is characterized by the generation of harmonics, a diminished voltage profile, and increased power loss in distribution transformers. In India, where EV adoption is rapidly growing, Level 2 AC charging schemes are predominantly employed for EV charging, utilizing a maximum current rating of 16 A and a maximum power rating of 3.3 Kw [5].
The EV charger considered in this project is a DC to DC 1.5 kw onboard battery charger SMCZ1 having maximum efficiency of 93%. It has the advantages of high efficiency, small size, high stability and long life. It also has the advantage of protection grade up to IP67 which can work safely under short time immersion condition. The full specifications of the battery are given below-

Table 2: Specifications of EV charger SMCZ1

SL No	Specifications	Technical Index
1	Working Temperature	-40°C to +60°C
2	Storage Temperature	-40°C to +90°C
3	Heat Dissipation mode	Forced Air Cooling
4	Input Voltage	AC 220V±15%
5	Input Frequency	60Hz±2%
6	Weight	3.8 Kg
7	Size	282x146x80 (mm^3)
8	Protection level	IP67

A brief discussion is given to comprehensively analyze the effects of EV charging on harmonics, voltage profiles, and transformer overloading, considering the dynamic and diverse landscape of the Indian power system.

METHODOLOGY

The main parameters in a distribution system are the Voltage Profile, Voltage Stability and Power Losses[6]. In this section we have done a brief discussion on how to calculate the voltage profile and voltage stability for standard IEEE 33 bus radial system. Further the effect of connecting VCS and DG in the 33 bus radial system is also elaborated here. Fig :3 shows a standard diagram of a IEEE bus radial distribution system [7].

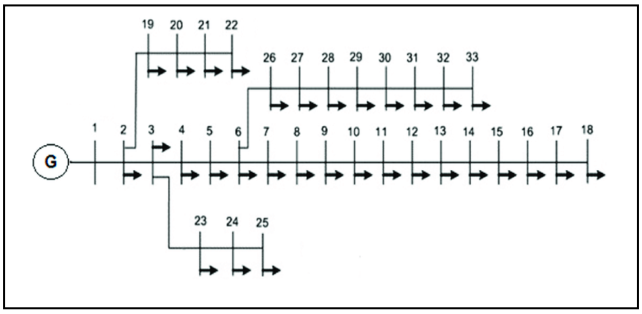

Fig 1: Single line diagram of IEEE 33 bus radial system

Forward and Backward sweep propagation method:

In case of distribution network the general method of doing load flow analysis is not suitable. So we are doing the conventional Forward and Backward sweep propagation technique to find out the voltage values and voltage profile of the standard IEEE 33 bus radial system. In the backward sweep, Kirchoff's current law is applied to calculate the current from the end bus to the substation. In forward sweep, voltage is computed from the substation to the end bus. When considering a distribution system with multiple feeders, at the junction bus, all the feeders connected to the bus should be considered for both forward and backward sweep [8].

Steps to perform distribution load flow are given below:

STEP 1: Start the process with the initial voltage at each bus as 1 pu.

STEP 2: Calculate the current at each bus based on the load connected using Equation (1)

$$I_i = \left(\frac{P_i + jQ_i}{V_i}\right)^* \qquad (1)$$

STEP 3: Backward sweep is performed to calculate the current flow from the ending bus to the starting bus, i.e.,

$(i + 1)^{th}$ bus to i^{th} bus, using Equation (2).

$$I_{(i,i+1)} = I_{i+1} + \sum branch\ current\ flowing\ from\ i^{th}\ bus \qquad (2)$$

STEP 4: The current from step 3 is used in the forward sweep to calculate the voltage at each bus using Equation (3)

$$V_i = V_{(i+1)} + I_{(i,i+1)} * Z_{(i,i+1)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

STEP 5: Steps 3 and 4 are repeated until the voltage value is converged to 10^{-6}.

Voltage Profile

After doing the load flow analysis we will get the values of bus voltages of the 33 bus radial system. The bus voltages for all the 33 buses are found out to be as follows –

Table 2: Voltage Magnitude and Angles

us Number	Voltage Magnitude *(pu)*	/oltage Angle *(radian)*
1	1.0000000	0.0000000
2	0.9970252	0.0001047
3	0.9828930	0.0007643
4	0.9753835	0.0014518
5	0.9679572	0.0021894
6	0.9494792	0.0011081
7	0.9459545	-0.0065375
8	0.9322986	-0.0127685
9	0.9259659	-0.0168021
10	0.9200918	-0.0205163
11	0.9192230	-0.0200470
12	0.9177082	-0.0192138
13	0.9115324	-0.0268572
14	0.9092424	-0.0349674
15	0.9078156	-0.0422574
16	0.9064336	-0.0473143
17	0.9043854	-0.0695227
18	0.9037721	-0.0737202
19	0.9964968	-0.0010666
20	0.9929192	-0.0105361
21	0.9922147	-0.0147241
22	0.9915773	-0.0234800
23	0.9793071	-0.0004170
24	0.9726356	-0.0042358
25	0.9693105	-0.0079935
26	0.9475496	0.0018161
27	0.9449853	0.0028517
28	0.9335435	0.0044388

29	0.9253237	0.0059749
30	0.9217656	0.0082328
31	0.9176035	0.0013413
32	0.9166879	0.0015157
33	0.9164042	0.0048697

These voltage values are found when there is no VCS or DG is connected in the distribution system. Later on the voltage values after connecting VCS (load) and DG with the base case will be compared. Different voltage profiles will be found for each cases [9]. The voltage profile and stability indices for different cases are analyzed

Voltage Stability Index

Voltage stability index is a numerical value used to evaluate the stability of a power system in terms of its ability to maintain acceptable voltage levels under normal and disturbed conditions . It helps in identifying the proximity of the system to voltage instability or collapse, which is critical for ensuring the reliable operation of the power grid[10]. There are various methods and indices developed for assessing voltage stability, some of the commonly used ones include:

1. **L-index:** This index is used to measure the voltage stability of a power system. It ranges from 0 (completely stable) to 1 (on the verge of instability). It is calculated based on the power flow solutions of the system and helps identify weak buses or lines in the network.
2. **Voltage Collapse Proximity Indicator (VCPI):** This index indicates how close a bus or the entire system is to voltage collapse. It is typically used in real-time monitoring and helps operators take preventive measures before instability occurs.
3. **Fast Voltage Stability Index (FVSI):** This index is used to quickly determine the stability condition of individual lines in the power system. It is particularly useful for large systems with multiple transmission lines[11].
4. **Line Stability Index (LSI):** This index assesses the stability of individual transmission lines. A higher value of LSI indicates a higher risk of voltage instability on that particular line.
5. **Z-index:** This is another index used to assess the voltage stability of power systems, especially in distribution networks. It is based on the impedance characteristics of the system.

Here we are going to use only the **fast voltage stability index** to analyze the effect of Vehicle Charging Station on voltage profile and voltage stability and further analyze the improvements after using Distributed Generation (DG) on the distribution network [12].

How to calculate Bus Voltage Stability Indices

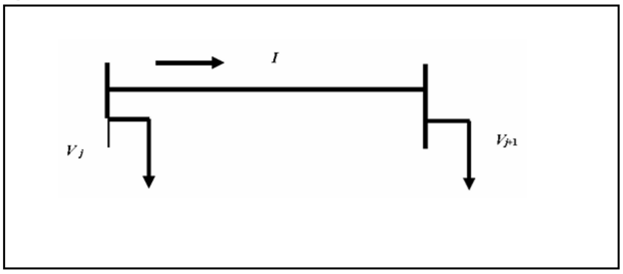

Fig 2: Single line diagram of a 2 bus system

buses of the system. $V_j < \delta_j$ and $V_{j+1} < \delta_{j+1}$ are the voltages at bus j and bus j + 1 respectively. I is the current flowing through the branch having resistance r and impedance x

$$I = \left(\frac{V_j - V_{j+1}}{r + ix}\right) \text{..................................... (4)}$$

$$P_{j+1} - iQ_{j+1} = V_{j+1}{}^{*} I \text{...............................(5)}$$

Substituting the value of I in equation (5) and equating the real parts and after further simplification we get equation (6)

$$V^4{}_{j+1} + 2V^2{}_{j+1}(P_{j+1}r + Q_{j+1}x) - V^2{}_j V^2{}_{j+1} + \left(P^2{}_{j+1} + Q^2{}_{j+1}\right) * |Z|^2 = 0 \text{ .... (6)}$$

From Equation (6) the transferrable active and reactive power can be written as in Equation (7) and Equation (8), respectively

$$P_{j+1} = \frac{M \pm \sqrt{N}}{|Z|} \text{ .... (7)}$$

Where, $M = -\cos\theta_z V^2{}_{j+1}$ *and*

$$N = \cos\theta_z{}^2 V^4{}_{j+1} - V^4{}_{j+1} - |Z|^2 Q^2{}_{j+1} - 2V^2{}_{j+1}x + V^2{}_j V^2{}_{j+1}$$

$$Q_{j+1} = \frac{P \pm \sqrt{Q}}{|Z|} \text{ .... (8)}$$

Where $P = -\sin\theta_z V^2{}_{j+1}$ *and*

$$Q = \sin\theta_z{}^2 V_{j+1}{}^4 - |Z|^2 P_{j+1}{}^2 - 2V_{j+1}{}^2 P_{j+1} r + V_j{}^2 V_{j+1}{}^2$$

$$N \geq 0, \quad Q \geq 0$$

Substituting the actual values of N, Q and adding them leads to the inequality defining the stability criterion of the system:

$$2V_j^2V_{j+1}^2 - 2V_{j+1}^2(P_{j+1}r + Q_{j+1}x) - |Z|^2(P_{j+1}^2 + Q_{j+1}^2 \geq 0 \ldots\ldots (9)$$

The value of Equation (9) is known as VSI. This is a criterion for determination of voltage stability [13].

Effect of Electric Vehicle Charging Station load on Distribution Network

The impact of EV charging load on voltage stability of IEEE33 bus test network is reported in this subsection. The value of VSI is calculated for all the buses by utilizing the methodology elaborated in section **5.2.1**. From the data collected from VSI calculation it is seen that the VSI value of **Bus 2** is the highest which is **0.9998** and VSI value of **Bus 18** is the lowest which is **0.6681**. Again, VSI value of Bus 19 is the second highest which is 0.9879 and VSI value of **bus 14** is **0.6891** which is one of the low values of VSI [14]. The lowest value of VSI is found in Bus 18 which is **0.6681**. So it is found that **Bus 2** and **Bus 19** are the strongest and second strongest bus of the distribution network and **Bus 18** is the weakest. EVCS are placed in different buses and the effects are analyzed here [15]. In this project 4 cases of placing the EV charging stations (capacity **1.5 KW)** are considered. The cases are –

A. **Base Case:** When no charging station is connected in the distribution
B. **Case 1:** When EVCS is placed on Bus 2 *(strongest bus)*
C. **Case 2:** When EVCS is placed on Bus 2 and Bus 19 *(strong buses)*
D. **Case 3:** When EVCS is placed on Bus 14 *(weak bus)*

**Since Bus 18 is the weakest bus, EVCS cannot be connected in this bus.If connected the voltage stability of the system will collapse and the system becomes unstable*

It can be seen that when EVCS is connected in Bus 2 and Bus 18 the voltage profile is not affected very badly by the additional load. The voltage profile becomes poor and VSI values also decrease. But when we consider Case 3 it is seen that the voltage profile becomes poorer and VSI values decrease drastically. So, it is clear that when Vehicle Charging Stations are installed in the distribution network the voltage profile becomes poorer and voltage stability decreases whether it is connected in strong bus or weak bus. But connecting EVCS in the weak buses affect the voltage stability and voltage profile more.

As the use of electric vehicles are increasing day by day the need for installing Electric Vehicle Charging Stations (EVCS) are also increasing. So this problem of affecting Voltage Profile and Voltage Stability must be mitigated by some means. Researchers have found that by placing Distributed Generations (DG) in different buses. These problems of Voltage stability can be mitigated upto a great extent. In this project the effects of using DG in the distribution network to improve voltage profile and system stability are analyzed.

5.3: Distributed Generations (DG)

Distributed generation (DG) refers to small-scale electricity generation technologies located close to the point of consumption. Unlike traditional centralized power generation, which involves large power plants and extensive transmission networks, distributed generation typically involves renewable and non-renewable energy sources that are integrated directly into the local distribution grid [16]

In this paper a DG of capacity 1 KW is used and connected in **Bus 14** (weakest bus) and analyzed the effects after using DG.

RESULTS AND ANALYSIS

A. Voltage Stability Index

In India the general capacity of a DG is 1KW.So, we have considered a DG of the same size and connected it in the 14th Bus as it is the weakest Bus . Again, load flow analysis is done as before and VSI values are calculated. It is found that after connecting DG in Bus 14 the voltage profiles of *Base Case*, *Case 1* and *Case 2* are improved greatly and VSI values also increased. In case of *Case 3* the voltage profile and stability is improved from before but the values are not so desirable [16].

In table 3, a brief comparison of VSI values before and after connecting DG is illustrated –

Table 3: VSI values before and after connecting DG

BUS NUMBER		VSI VALUES			
		BASE CASE: (WITHOUT VCS)	CASE 1; (VCS AT BUS NO 2) ***[strong bus]***	CASE 2 (VCS AT BUS NO 2 &19) ***[strong buses]***	CASE 6 (VCS AT BUS NO 14) ***[weak bus]***
1	WITHOUT DG	0	0	0	0
	WITH DG	0	0	0	0
2	WITHOUT DG	0.9998	0.9981	0.9981	0.9998
	WITH DG	0.9998	0.9981	0.9981	0.9998
3	WIT	0.9867	0.983	0.9798	0.980

	HOI UT DG		3		9
	WIT H DG	0.9895	0.986 1	0.9826	0.984 9
4	WIT HOU T DG	0.9324	0.929 0	0.9257	0.902 2
	WIT H DG	0.9476	0.944 3	0.9409	0.923 0
5	WIT HOU T DG	0.9046	0.901 3	0.8980	0.857 3
	WIT H DG	0.9288	0.925 4	0.9221	0.889 8
6	WIT HOU T DG	0.8759	0.872 6	0.8694	0.810 4
	WIT H DG	0.9096	0.906 3	0.9030	0.855 3
7	WIT HOU T DG	0.8116	0.808 4	0.8053	0.714 6
	WIT H DG	0.8627	0.859 5	0.8562	0.780 7
8	WIT HOU T DG	0,7950	0.791 9	0.7888	0.686 1
	WIT H DG	0.8504	0.847 2	0.8440	0.700 1
9	WIT HOU	0.7545	0.751 5	0.7485	0.588 8

	WITHOUT DG				
	WITH DG	0.8465	0.8433	0.8401	0.6685
10	WITHOUT DG	0.7342	0.7312	0.7282	0.5375
	WITH DG	0.8480	0.8448	0.8416	0.6401
11	WITHOUT DG	0.7166	0.7136	0.7107	0.4921
	WITH DG	0.8522	0.8490	0.8458	0.6352
12	WITHOUT DG	0.7137	0.7107	0.7078	0.4842
	WITH DG	0.8535	0.8503	0.8471	0.6254
13	WITHOUT DG	0.7078	0.7049	0.7019	0.4677
	WITH DG	0.8556	0.8524	0.8492	0.5848
14	WITHOUT DG	0.6891	0.6862	0.6833	0.4091
	WITH DG	0.8678	0.8646	0.8613	0.5977
15	WITHOUT	0.6830	0.6802	0.6773	0.3979

	DG				
	WITH DG	0.8732	0.8699	0.8667	0.5814
16	WITHOUT DG	0.6786	0.6757	0.6729	0.3945
	WITH DG	0.8816	0.8783	0.8750	0.5882
17	WITHOUT DG	0.6739	0.6710	0.6682	0.3909
	WITH DG	0.8933	0.8900	0.8867	0.5977
18	WITHOUT DG	0.6681	0.6652	0.6624	0.3865
	WITH DG	0.9255	0.9222	0.9188	0.6240
19	WITHOUT DG	0.9879	0.9845	0.9780	0.9829
	WITH DG	0.9904	0.9869	0.9804	0.9864
20	WITHOUT DG	0.9837	0.9802	0.9707	0.9787
	WITH DG	0.9861	0.9827	0.9732	0.9821
21	WITHOUT	0.9713	0.9679	0.9584	0.9664

	DG				
	WITH DG	0.9737	0.9703	0.9609	0.9698
22	WITHOUT DG	0.9680	0.9646	0.9551	0.9631
	WITH DG	0.9704	0.9670	0.9576	0.9665
23	WITHOUT DG	0.9326	0.9292	0.9259	0.9028
	WITH DG	0.9477	0.9443	0.9410	0.9233
24	WITHOUT DG	0.9135	0.9101	0.9068	0.8840
	WITH DG	0.9284	0.9251	0.9217	0.9043
25	WITHOUT DG	0.8888	0.8856	0.8823	0.8597
	WITH DG	0.9036	0.9003	0.8970	0.8798
26	WITHOUT DG	0.8125	0.8094	0.8063	0.7156
	WITH DG	0.8637	0.8604	0.8572	0.7816
27	WITHOUT	0.8059	0.8028	0.7996	0.7094

	DG				
	WITH DG	0.8568	0.8536	0.8504	0.7751
28	WITHOUT DG	0.7961	0.7930	0.7899	0.7001
	WITH DG	0.8467	0.8435	0.8403	0.7655
29	WITHOUT DG	0.7577	0.7547	0.7517	0.6642
	WITH DG	0.8072	0.8041	0.8009	0.7279
30	WITHOUT DG	0.7304	0.7274	0.7244	0.6385
	WITH DG	0.7789	0.7758	0.7728	0.7010
31	WITHOUT DG	0.7196	0.7166	0.7137	0.6285
	WITH DG	0.7678	0.7648	0.7617	0.6905
32	WITHOUT DG	0.7079	0.7050	0.7020	0.6175
	WITH DG	0.7557	0.7527	0.7497	0.6790
33	WITHOUT	0.7057	0.7028	0.6998	0.6155

	DG				
	WITH DG	0.7534	0.7504	0.7474	0.6769

B. Voltage Profile

Doing the load flow analysis after connecting the DG in different buses it is found that the voltage profiles in Base Case, Case 1 and Case 2 are improved but In Case 3 voltage profile is improved but the values are not desirable as VCS is connected in the weak bus [16].

A comparison of voltage profiles in each cases are shown in the following graphs –

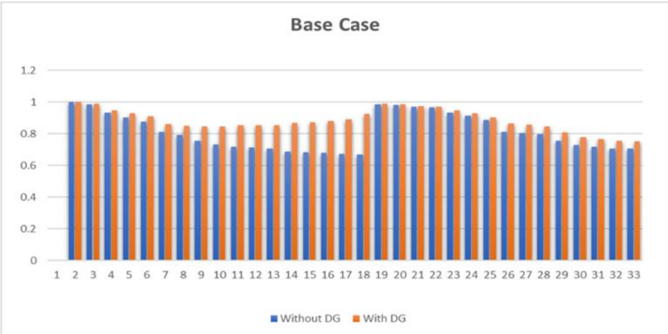

Fig 3: Comparison chart for base case

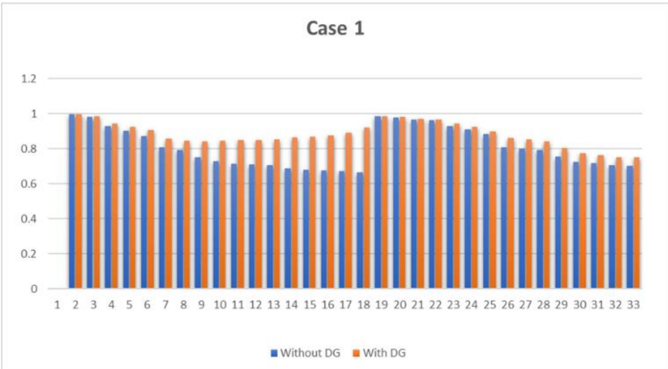

Fig 4: Comparison Chart for Case 1

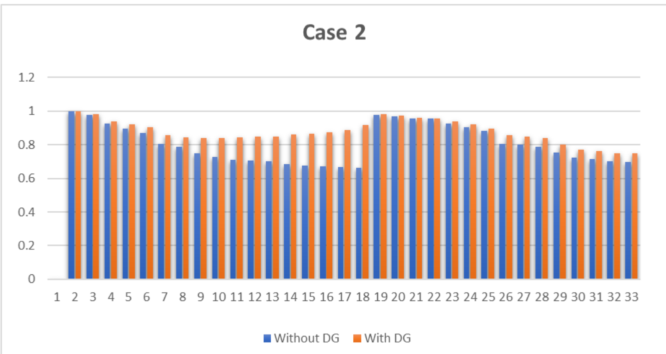

Fig 5: Comparison Chart for Case 2

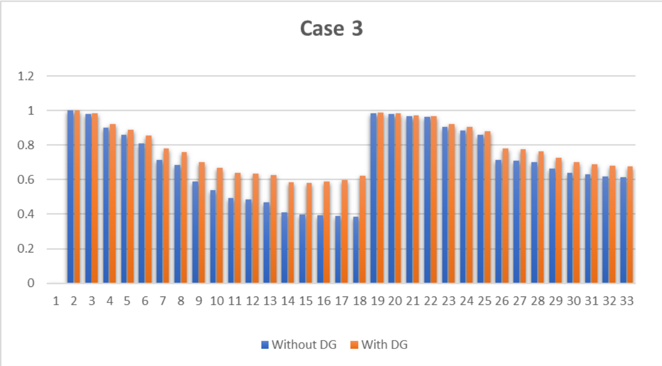

Fig 6: Comparison Chart for Case 3

CONCLUSION

EVs are a favorable alternative to reduce the emissions of the transport sector. The growing popularity of EVs has led to the establishment of Electric Vehicle Charging Stations (EVCS); however the detrimental impact of the resulting EV charging station loads on the distribution network cannot be neglected. This work meticulously analyzed the impact of EV charging station loads on the voltage stability and voltage profile of IEEE 33 bus test system. The results obtained showed that the impact of placing fast charging stations at the weak buses affected the smooth operation of the power distribution network. However, the system was strong enough to withstand the placement of charging stations at the strong buses. But, when the charging stations are placed at the weak bus it affected the voltage stability and voltage profile vastly. It is found that using a DG of required size these problems of voltage instability and poor voltage profile can be mitigated upto a great extent Thus, this work will serve as a guide to the power system engineers and help in planning of distribution networks in presence of EV charging loads .

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