Improving Power Quality of Distributed PV-EV Distribution Grid by Mitigating Unbalance

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Abstract*-- Fuel-based transport system and electricity generation system emit a higher amount of greenhouse gasses which increase global warming. Increasing price of fossil fuels and public awareness encouraged many countries to use clean technologies in transport and electricity generation sector. The advent of smart meters can identify unbalance in PV-EV distribution grid which is a great concern for Distribution Service Operators (DSOs). Several researchers have accessed the degree of unbalance and impact of unbalance on distribution grids considering either distributed PV or EVs. Moreover, a few research work has been done for mitigating unbalance till now. This paper measures unbalance due to unequal distribution of loads and sources among three phases and assess the impact of unbalance on power quality of the PV-EV distribution system by considering different PV and EV penetration levels using DigSILENT Power Factory simulation software. An improved method is proposed to mitigate unbalance using Genetic Algorithm by optimizing load distribution among phases. Finally, the efficacy of the proposed method is evaluated considering unequally distributed residential and EV load scenarios, and it is found that the proposed method can reduce a significant amount of unbalance at all the buses of the distribution grid.

***Index Terms*- Unbalance, PV, Electric Vehicle, Unbalance Mitigation, Genetic Algorithm, Distribution Grid, Distributed Generators.**

I. INTRODUCTION

Due to the integration of distributed generation and new loads, for example, electric vehicle, current low-voltage distribution grid is facing several challenges. The advent of smart grids is making distribution grid more intelligent and reliable. The smart grid uses pre-post information through extensive monitoring devices, communication, and control technologies to operate distribution grid efficiently. The induction of smart monitoring system in smart grid provides valuable information's such as various losses, harmonic distortions, and level of voltage unbalance to distribution service operator for analyzing power quality, cost, generation-demand control and different types of fault **[1]**. Distributed generators such as PV solar roof-top plants and new loads like Electrical Vehicles are connected to Distribution grid rather than transmission grid and induces three-phase voltage imbalance at LV distribution grids. Voltage imbalance reduces available capacity by increasing neutral current, higher voltage drop, minimize utilization of network asset which increases reinforcement cost [2-4].

The authors in [5] report that 12 million electric vehicles have been sold and pre-ordered whereas estimated sells will increase 200 million in 2030. The growing energy demand due to EVs can be meet up with distributed PV solar units and wind power systems rather than conventional fossil fuel technologies [4, 6, 7]. The advantage of EVs is its own battery capacity which is used as storage or backup to manage balancing the supply-demand of the grid. Vehicle to Grid (V2G) technology is an efficient way to mitigate the uncertainty of renewable energy sources, especially PV solar and wind energy and assist grid through different charging and discharging scheduling [8-12] .

The rapidly integrating distributed energy resources (PV solar and EV storage) and sudden EVs demand with residential loads are making LV distribution grid more unbalance. Due to increased distributed single-phase PV integrations, phase imbalance and fault current [13] are increased. Unplanned placement and sizing of distribution PV plants increase voltage imbalance [14]. The work in [15] shows the integration of distributed PV units and EVs in residential grid increases voltage imbalance in distribution feeders and power imbalance at the transformers. The authors of [16] investigate the effect of PV and EV systems at different unbalanced loading level on energy loss and voltage profile of a distribution grid by using forward-backward sweep algorithm. Another example [17] of dynamic load flow studies shows transformer over-loading, energy losses, and current imbalance increases after incorporating PV and EV on the distribution grid. Though both the deterministic and probabilistic [18-20] methods were used to investigate EVs impact on PV-EV distribution grid assuming balance system, a few research work has focused to mitigate unbalance on the distribution grid. The author proposes particle swarm optimization (PSO) algorithm for coordinating EVs charging-discharging to mitigate imbalance assuming balanced residential- unbalanced EV distribution grid [21].

Most of these existing technical analyses assumed that EV owners would charge their vehicles during night time, however financial studies in [22] show utilizing PV solar energy for charging EVs can maximize benefits by reducing fuel and electricity production cost. In previous literature studies, researchers assumed residential balanced network, low (1.8-3.7 kWh) charging power of EVs of a distribution network and avoid the impact of uncertainty of distributed PV units during coordinated EV charging/discharging. But the uncertainty of distributed PV induce the voltage unbalance [23] in small distribution grids, and higher EV power train (> 15 kWh) is available in the recent EV market. The evolutionary algorithm PSO for mitigating unbalance assumed EV variable power charging-discharging scenario whereas consumers are not bounded by DSOs to discharge their EVs at a certain period.

In this paper, most popular electric vehicle Tesla Model S is considered with 17 kWh constant charging power consumed from distribution grid. Distributed PV systems with its different penetration level are considered for analyzing the uncertainty characteristics of PV systems. This paper proposes a method to mitigate system's unbalance using Genetic Algorithm by considering largely unbalanced residential and EV loads (connected EVs in charging mode). Finally, the performance of the proposed method is compared with an existing method to mitigate system's unbalance. The rest of the paper is organized as follows.

Detail modeling of the proposed system is provided in Section II. Case studies to show the impact of distributed PV, and EVs on a LV distribution grid's unbalance by considering different scenarios are given in Section III. A method to mitigate system's unbalance is provided in Section IV and its performance is investigated in Section V. Section VI includes the summary and future direction of this research work.

II. SYSTEM MODELLING

A. PV system

In this paper, the generic PV system model in DigSilent Power Factory 2017, Sun Power 455 J WHT D (peak MPP power - 455 W) is used for simulating the distribution grid. The roof-top PV plant is located in New South Wales, Australia and most of the PV panels are north faced with an installed capacity of 5 kW. The PV output power within the proposed simulation grid is assumed to have similar PV output power characteristics because nearly all the distributed PV plants experience the same variability [24]. The output PV penetration level is defined as –

$$PV\ Penetration = \frac{PV\ power\ output\ to\ Distribution\ Grid}{PV\ installed\ capacity} \qquad (1)$$

The uncertainty of PV power is replicated through PV penetration/islanding into the distribution grid. Three phase PV system is considered to inject unequal power among phases for measuring unbalance degrees. The PV system increases the generation capacity of a distribution grid and creates opportunity to recharge EVs with reduced residential loads during the daytime.

B. EV system

Nowadays, EVs are popular for their increased millage, reduced battery cost, and safety benefits. EV owners will use battery swapping/community sharing benefits for charging EVs to maximize the benefits of PV solar power. In this paper, the most popular Tesla EV Model S is used which has 85 kWh battery storage providing a driving mileage of over 265 miles [25] . Tesla EV Model S requires 5 hours to gain 100% State of Charge (SOC). This feature indicates that EVs can consume or supply 17 kW per hour from/to grid depending on its mode of operation. EVs are modeled as 17 kW, unity power factor loads which are distributed among three phases. PEVs are also modeled as batteries which have the storage capacity of 17 kW. The uncertain instantaneous EV load in the distribution grid is expressed as EV penetration which is defined as –

$$EV\ Penetration = \frac{EV\ charging\ load\ in\ kW}{Installed\ EV\ capacity} \qquad (2)$$

C. Simulation Grid

In this paper, IEEE-13 node residential grid (LV distribution prototype) is replicated using simulation software DigSilent Power Factory 2017 for analysis. The network is assumed to be located at densely populated area which supplies electricity to 492 households and 196 PEVs. It is assumed that the total household PV power of 750 kW, 0.9 p.f. lagging is supplied to the distribution network. The distributed PV solar plant, residential and EV loads are connected to the grid (presented as External Grid) through a transformer rated at 10 MVA, 11/.4 kV with different nodes of distribution grid. The Bus named UNB 650 is considered as the point of common coupling (PCC) node to connect this distribution network to the grid through a two-winding transformer.

D. Evaluation Indices

In a balanced power system, electrical quantities such as phase impedances must be equal and the neutral current must be zero. In the practical distribution system, it is not possible to maintain the LV distribution system balance due to uncertain distributed generations and instantaneous EV's demand. Nowadays, owing to the deployment of smart meters, it is possible to monitor the unbalance. To quantify unbalance of the distribution system, different indicators as shown in Table I. are used. The authors of [38] examined suitability of various indicators such as Line Voltage Unbalance Rate (LVUR), Phase Voltage Unbalanced Rate (PVUR) and Voltage Unbalance Factor (VUF).

In this paper, the most commonly used indicator VUF is used for analysis to understand degree of unbalance during power flow computation.VUF is defined as the ratio between negative sequence components (voltage/current/power) and positive sequence components (voltage/current/power). For voltages, the following equation is used for VUF.

$$VUF = \frac{Absoulute\ value\ (Negative\ Sequence\ Voltage)}{Absolute\ value\ (Positive\ Sequence\ Voltage)} \qquad (3)$$

For a symmetrically balanced system, VUF is zero. VUF magnitude will increase if ratio of negative sequence to positive sequence voltage increase. The unbalance indicator VUF at any node of a distribution grid also resembles the unbalance degree of the connected distributed source and loads characteristics.

TABLE I Various Key Indicators of Voltage Unbalance [26]

Standard	Unbalance Indicators
Institute of Electrical and Electronics Engineering Std. 141-1993	Phase Voltage Unbalanced Rate (PVUR)
National Equipment Manufacturer's Association MG1-1993	Line Voltage Unbalance Rate (LVUR)
Institute of Electrical and Electronics Engineering Std. 1159-2009	Voltage Unbalance Factor (VUF)

III. CASE STUDY

Smart grid interconnected with distributed generations and mobile loads which differs from the conventional grid in different ways. In smart grid, smart meter technology creates an opportunity to investigate causes of power quality degradation. It is identified that variable PV power and instantaneous PEVs create unbalance in the distribution grid. In the previously published literature, quantification of unbalance factor due to the integration of both PV and PEVs into unbalanced residential distribution grids are not analyzed in detail. To analyse impact of unbalance due to PV and PEVs on power quality of distribution grid, several scnarios are simulated and discussed in the following subsections.

A. Impact of Distributed PV penetration without EVs

The aim of this scenario is to investigate the impact of distributed generations on voltage unbalance and analyze its effects on power quality. The distribution network supplied 492 households assumed sixty percent loads during the day with 1.9 kW active power in each home, 0.9 p.f. lagging residential loads which are distributed among phases (Phase A: 24 households, Phase B: 123 households and Phase C : 345 households) in such a way to make the network more unbalance. The impact of PV penetration on voltage unbalance, minimum node voltage and maximum voltage drop along feeder expressed as network loss are shown in below Fig. 1, Fig. 2 and Fig. 3.

In this simulation, five different PV penetration scenarios are considered for the analysis. Fig. 1 shows minimum bus voltage which gradually increases with PV penetration and higher bus voltage occur at 100% PV penetration.

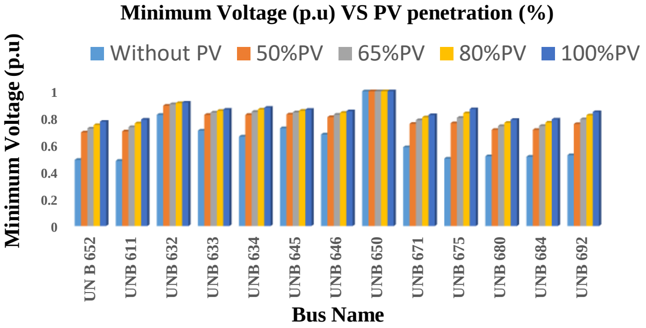

Fig. 1. Minimum Voltage (p.u) at different Bus with different PV penetration.

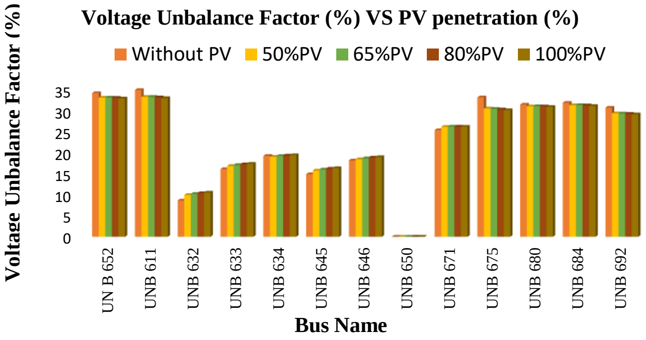

Fig. 2. Voltage Unbalance Factor (%) at different Bus with different PV penetration.

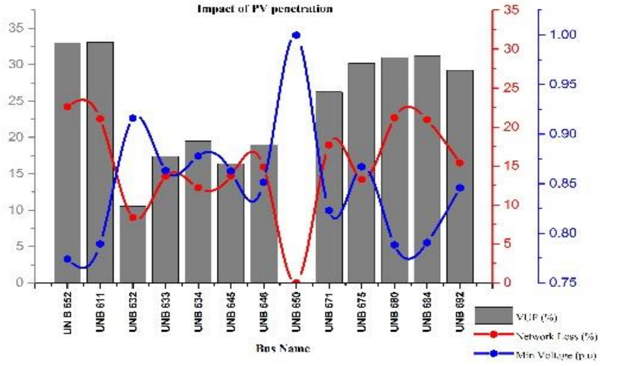

Fig. 3. Voltage Unbalance Factor (%) and Minimum voltage (p.u) at different buses after PV integration (PV penetration 100%).

This result shows the distributed generation increases the minimum bus voltage whereas it has less impact on VUF as shown in Fig. 2. Both the minimum Bus voltage and network loss depend on VUF as shown in Fig. 3. The simulation result shows the network loss increases when the unbalance increases in the distribution grid. The minimum bus voltage increases when VUF is less, which indicates the power quality depends on VUF.

B. Impact of Distributed EV Penetration on PV-EV Distribution Grid

The objective of this scenario is to analyze the impact of EV penetration in the charging mode. To analyze the impact of PEVs penetration, Tesla EV Model S is distributed among phases (phase A: 12 EVs, Phase B: 49 EVs and Phase C: 135 EVs) to make the distribution grid more unbalanced. EVs are assumed to consume constant electric power 17 kWh from the distribution grid. The impact of PEVs penetration on voltage unbalance, minimum node voltage and network loss are shown in Fig. 4, Fig. 5 and Fig. 6.

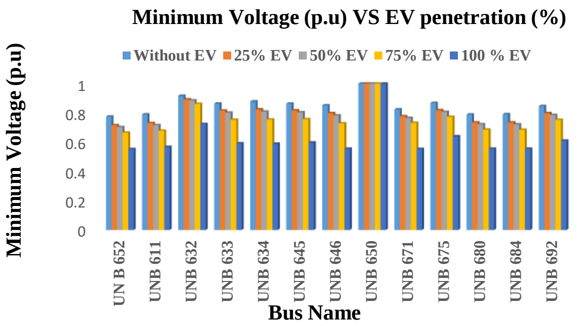

Fig. 4. Minimum Voltage (p.u) at different Bus with different EV penetration.

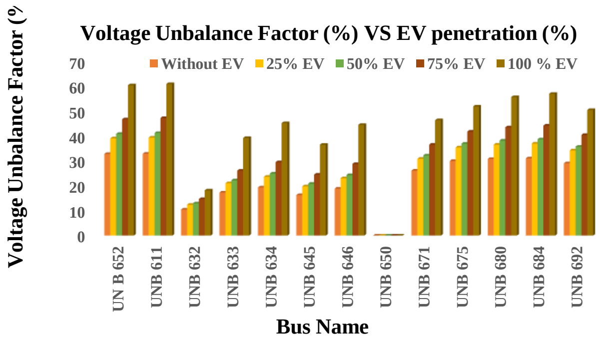

Fig. 5. Voltage Unbalance Factor (%) at different Bus with different EV penetration.

The simulation result analyses the impact of EV penetration considering five different scenarios. The EV penetration resembles instantaneous large loads integrated into the network, and it gradually reduces the minimum bus voltage (p.u) at every bus of the distribution grid. Lower minimum voltage (p.u) is observed during 100% EV penetration which is below 0.6 at some buses which is a major issue for DSO's. The EV penetration sharply decreases the minimum bus voltage and increases the imbalance at all buses as shown in Figs. 4-5. The integration of EVs also reduces the system capacity by increasing the network loss as the degree of unbalance increase as shown in Fig. 6. The result shows that the minimum bus voltage also depends on the distribution system unbalance. This simulation scenario indicates that instantaneous large EV loads induce imbalance in the grid which decreases the power quality and reduces the capacity.

C. Impact of Distributed PV Islanding on PV-EV Distribution Grid

This scenario investigates the variability characteristics of PV power and analyses the impact on power quality. The simulation task assumes that 100% of EVs are charging and 50% PV is islanding. The simulation results in Fig. 7 shows a small amount of change in unbalance induces the higher increase in minimum bus voltage. Though the VUF (%) at some buses decreases (represented by the negative sign) after islanding, the minimum bus Voltage increases (8%-24%) at all the Bus.

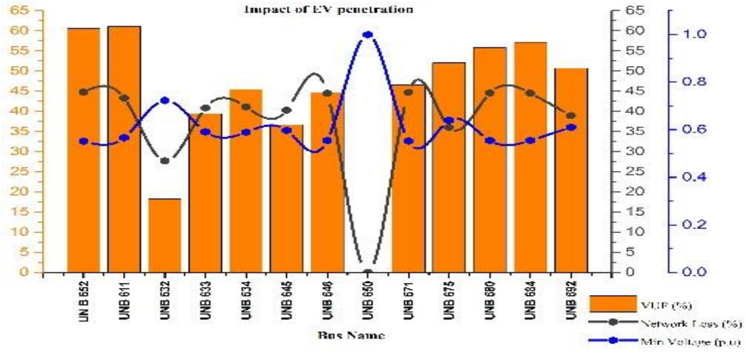

Fig. 6. Voltage Unbalance Factor (%) and Minimum Voltage at different Bus after EV integration (EV penetration 100%).

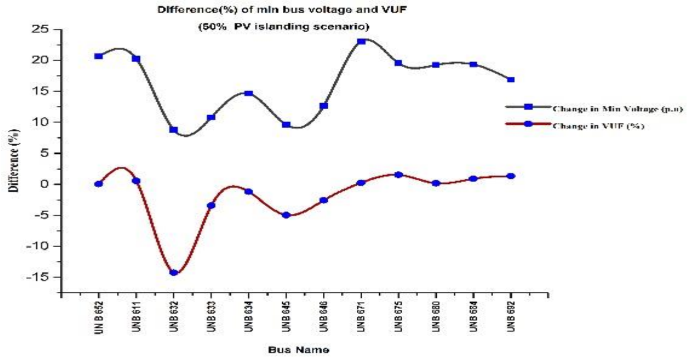

Fig. 7. The difference (pre-post islanding scenarios) of minimum bus voltage and Voltage Unbalance Factor at different Bus.

D. Impact of EV Charging-Discharging Mode on PV-EV Distribution Grid

This simulation scenario resembles vehicle to grid (V2G) technology. EVs are connected in charging and discharging mode with distributed PVs. EVs are charging at constant charging power (17 kWh) and discharging at Depth of Discharge (DOD) setting of 60% to enhance the battery lifetime. The impact of distributed EV penetration in both charging and discharging modes on the voltage unbalance in distribution grid are shown in Fig. 8 below.

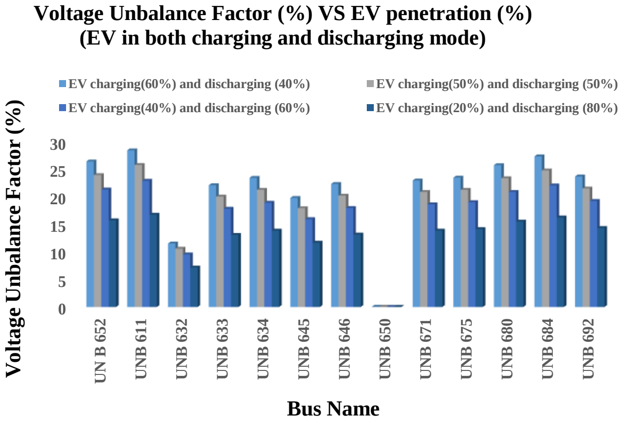

Fig. 8. Voltage Unbalance Factor (%) VS EV penetration while EVs in charging and discharging modes at 100% PV penetration.

The result shows that the increasing penetration of EVs in discharging mode benefits DSOs by reducing unbalance. On the contrary, reduction in EV penetration in charging mode also reduce the voltage imbalance. It is also observed that EV charging mode (20%) and discharging mode (80%) requires almost no power import from the grid but the value of imbalance indicator VUF is large. The VUF at Bus 611 is 16.73% which is still high in spite of integrating higher penetration of distributed generations (PV and EV storage).

IV. PROPOSED METHOD

The above case studies show that the increasing distributed generations penetration (PV penetration) and scheduling of EVs (V2G) cannot reduce the significant amount of imbalance of a distribution grid having the higher un-optimized distribution of loads among phases. This paper proposes a method to improve the power quality by mitigating unbalance using Genetic Algorithm (GA). GA is a biological evolutionary heuristic search algorithm to systematically optimize a method [27] . GA is useful where variables are discrete, and constraints are explicit. In this paper, GA is applied to optimize residential and EV load distribution among three phases to gain lowest VUF which is also expressed as optimization condition at the worst bus. The aim of the proposed method is to optimize loads among phases without changing the total load capacity per bus rather than re-phasing all the loads in the distribution grid as stated in previous works of literature which may change utilization capacity of the power devices (transformer, CB, etc.) in the distribution grid.

The proposed method is described below -

Step 1: Run Unbalanced Load Flow in DigSilent Power Factory software environment.

Step 2: Calculate Voltage Unbalance Factor (VUF) at different buses using equation (3).

Step 3: Rank bus matrix according to the VUF value and determine the worst bus.

Step 4: Start DPL script of Genetic Algorithm in DigSilent Power Factory.

Step 4.1: Generate the initial population.

Step 4.2: Run Unbalanced Load Flow.

Step 4.3: Check optimization condition.

Step 4.4: If not satisfied, regenerate population and repeat Step 4.2 to 4.4.

Step 4.5: If satisfied, exit the program.

Step 5: Write the optimized loads to the output text file.

These steps are executed in DigSilent Power Factory using DPL script and will investigate power quality for comparing with the existing scenarios in the next section.

V. EVALUATION OF THE PROPOSED METHOD

In this paper, different scenarios are analyzed to investigate the network unbalance and its impact on the power quality. Among the above scenarios, the higher penetration of PEVs into distribution grid increases unbalance and decreases the network quality.

The highest VUF (61.062%) is observed at bus 611 and minimum bus voltage degrades to 0.56 p.u. at 100% EV penetration. The proposed method is applied to the distribution grid considering the 100% EV penetration scenario, and the VUF 3.6% at bus 611 is obtained. The proposed algorithm not only reduces 93% unbalance at Bus 611, but also optimizes other nodes. The proposed algorithm leads to a new distribution of loads among phases without changing the total loads per bus as shown in Table II and the comparative results of the VUF at different buses as shown in Fig. 9.

TABLE II PROPOSED LOAD DISTRIBUTION USING GENETIC ALGORITHM

BUS Name	Total Loads per BUS		Phase A				Phase B				Phase C			
			Existing		Proposed		Existing		Proposed		Existing		Proposed	
	RES	PEV	RES	PEV	RES	PEV	RES	PEV	RES	PEV	RES	PEV	RES	PEV
NODE 611	37	17	2	1	10	1	9	4	2	12	26	12	25	4
NODE 632	43	17	2	1	30	12	11	4	2	1	30	12	11	4
NODE 633	59	24	3	1	15	17	15	6	4	1	41	17	40	6
NODE 634	37	15	2	1	9	10	9	4	2	4	26	10	26	1
NODE 645	41	19	2	1	29	13	10	5	10	1	29	13	2	5
NODE 646	39	15	2	1	10	4	10	4	2	1	27	10	27	10
NODE 652	33	14	2	1	2	9	8	3	8	1	23	10	23	4
NODE 671	43	16	2	1	30	1	11	4	11	4	30	11	2	11
NODE 675	31	12	1	1	2	3	8	3	8	1	22	8	21	8
NODE 680	44	15	2	1	11	10	11	4	2	4	31	10	31	1
NODE 684	47	19	2	1	33	14	12	5	12	4	33	13	2	1
NODE 692	38	13	2	1	9	1	9	3	27	3	27	9	2	9

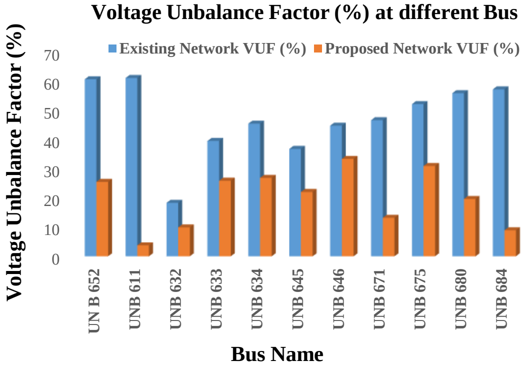

Fig. 9. Voltage Unbalance Factor (%) at different buses (A comparative study between the existing network and proposed network).

VI. CONCLUSION

The impact of PV units and EV systems on the unbalance effects of a low-voltage distribution system is investigated in this paper. It is found that distributed unbalanced PV units and EVs have significant impact on the voltage unbalance in the distribution grid. Four scenarios with unequally distributed loads among phases have considered quantifying unbalance indicator and impact of voltage imbalance on bus voltage and energy loss in the distribution system. After analyzing the results of different scenarios, it can be concluded that the distributed PV penetration slightly decrease VUF but increase the significant amount of Bus voltage whereas EV penetration increases the substantial amount of VUF (above 50%) and decrease Minimum Bus voltage (below 0.6 p.u.). The effect of uncertain characteristics resembled through islanding which shows the slight change in VUF but decreases the significant amount of Bus voltage. The impact of V2G technology does not show enough contribution to reducing VUF (above 20%) though they are equally penetrated in the distribution system. From these scenarios, it is realized that the system unbalance decreases the bus voltage and increases the system loss, which should no longer can be ignorable for DSOs. In this paper, a method is proposed to mitigate the unbalance and evaluated by considering the worst case (EV penetration 100% and VUF at Bus 611 is 61.062%). The GA is applied to optimize both residential and PEV loads among phases, leading to the reduced VUF (3.6%) at Bus 611. The proposed method using GA reduces VUF at the target bus by 93%. It is proposed to study the effectiveness of multi-objective evolutionary algorithms to mitigate the unbalance in the PV-EV distribution grid for future analysis.

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