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Ancillary Service of Voltage Support for a Weak Medium Voltage Grid through Injected Distributed Generation

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Abstract—Voltage Stability & Control, is very crucial compared to other Power System (PS) Quality and Stability issues. Long-Vertical-Power-Flows in Conventional Grids, causes voltage drops which in turn causes huge power losses, especially in the Medium Voltage (MV) and Low Voltage (LV) Distribution Networks. Such technical losses in abysmally-planned weak distribution networks, lead to substantial loss of revenues to the utility grid. Apart from classic Voltage Regulation (VR) techniques, with the rise of Distributed Generation (DG) based on Renewable Energy Sources (RES), Horizontal-Power-Flows can be introduced in the network, through various Smart Grid techniques. Coupling such sources, near load centers shall mitigate long flows from expensive conventional sources at times of huge demands, improving feeders' Voltage Profile. This Ancillary Service of Voltage Support from DG RESs shall thereby alleviate revenue losses caused by long-power-flows in weak distribution grids. For a developing country like Pakistan, loss of revenue from an already expensive utility gives huge blow to the economy. So, a similar technique for voltage support is proposed for an 11-kV feeder, which faces similar problem, and the results are remarkable. The technique is implemented using OpenDSS Tool by modelling 3MWp PV Penetration along with some future storage.

Keywords— ***Voltage Regulation (VR), Distributed Generation (DG), Renewable Energy Sources (RES), Voltage Regulation (VR), Ancillary Service***

1. INTRODUCTION

Despite significant investment in central power generation in third world countries (like Pakistan), over the last years Electricity consumers still face power outages and low power quality. The situation will not improve with more central power generation of the High-Voltage (HV) 132-500kV Grid as the electricity has to be routed through the MV 11-kV grid (in a conventional-vertical-manner), which causes the long power flows that leads to extreme voltage drops. Further, due to poor planning caused by poor load forecasting, Distribution Networks that includes MV & LV Lines and Distribution transformers are often overloaded and losses very high - Weak Grids. The situation is especially worsening at the end of long distribution lines where the load centers are located usually. In future this situation will further deteriorate with population growth, and with upcoming Plug-in-Electric Vehicles (EVs) will rise demand of the population already having an electricity connection. Poor infrastructure planning and reluctance in implementing Distributed Renewable Technologies Sources, the Distribution Power Utility are facing huge amount of power unit recoveries causing incremental fall in revenue Generation and rise of Circular Debts, which are consider as economy killer. While the rest of world incentivizing RES sources, there is a rise in consumers with DG Units based on RES connected to grid. Critical Studies [1] & [2] on power systems quality, have shown that this has helped not only them to lower their grid dependence (in terms of energy demand) but have also supported their gird in terms voltage and frequency support.

This is possible and studied in [3-4] when instead of conventional power flow i.e. from central generation, power flow neighboring sources and loads took place, what we like to call: "Horizontal Power Flow", which unburdens the distribution feeders and improves the Voltage Profile as per the Grid Code limitations.

Now this phenomenon of Horizontal Power Flow could be extended on a large scale where DG sources could suffice local load centers of the weak grids to avoid long power flows and improving the Voltage Profile. Such services are known as Voltage Support Ancillary Services to Distribution System Operator. The power system regulator may device some payment mechanism for such services to the grid. Public & Private entities can take part in such services by proposing their DG Plants being connected to the Grid compliant to the Grid Code. Which the scope of this paper is limited only to the technical aspect of this novel grid support.

Considering the case of Pakistani DISCOs, which are responsible for keeping and upgrading the distribution grid, face severe profitability due to the similar technical losses of Weak grid. Distribution lines are sometimes as high as 25% for some feeders on some summer days [5-6]. Above 144 million Pakistanis don't have reliable access to electricity due to a lack of reliable connection to the national electricity grid (44%) or due to blackouts that can last over 12 hours per day. Such issues can't be resolved by enhancement of distribution infrastructure completed as it cannot afford a major improvement of the 8,000 Weak Grid lines in the country. Pakistan itself is short of foreign reserves and needs to provide more electricity for productive use, especially in the countryside, to allow improved productivity and finally exports of goods, be it textile or agricultural produce. As the situation is better in the cities, people migrate to cities which leaves the land deprived of the higher potential youth and create even bigger cities which are difficult to control.

For this purpose, the technique is being proposed for voltage regulation support by implemented on a weak MV feeder of 11 kV feeder in Lahore, the Gohwindi feeder near Lahore Airport, with a total line length of 107km using a powerful tool – OpenDSS, which is a Smart Grid technique Modelling Platform for Distribution Power Networks.

VR Problem and its various classical mitigation techniques with short coming are discussed in Heading 2. In Heading 3 the proposed methodology for VR Support is explained. Heading 4 is an introduction to OpenDSS with Implementation & Results of the technique on the Gowindi feeder.

2. VOLTAGE REGULATION PROBLEM AND CLASSICAL SOLUTIONS

2.1. The Problem

Any demand on the grid causes flow of current from a source to a load suffers voltage drops along the distribution lines, each line being associated with characteristic impedance Z [7], depending upon its length and size (Ohms law V = I Z). Following that each voltage drop is associated with Power Loss ($P = I^2 Z = V^2 / Z$), greater is the load current and farther its location from source, more is the voltage drop Fig.2. This accounts for the loss of recoveries in units consumed by the consumers on behalf of the utility, known as 'technical losses'. Shown in Fig.1&2

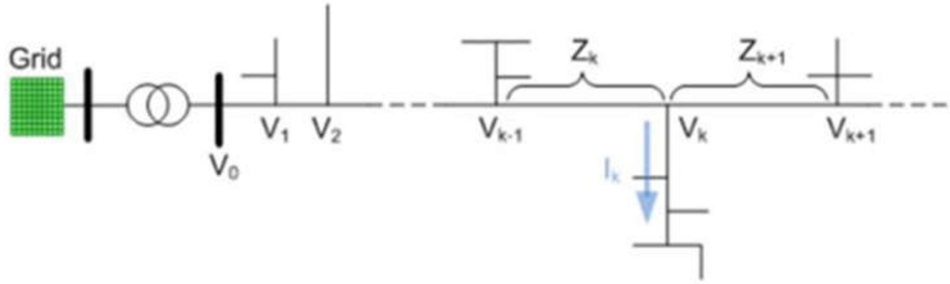

Fig 1 V_0 is the Source Bus and other are Load Buses

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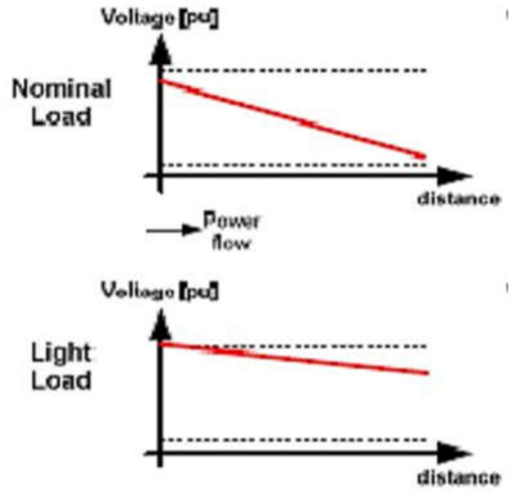

Fig 2 Effect of Load & Distance on Voltage Drop

Now depending upon the nature of load, Power (current) flow due to that load can be either Active or Reactive Power. While each do cause power losses in form of voltage drop, both of them have different affects and mitigation techniques. While this paper is focused on Power Losses from active powers.

Every Voltage drop is followed by tripping of Connected Loads and further decrease in revenue for utility. Undersized feeders and poor future load-forecasting is the main reason of Voltage Drops and Power Losses.

2.2. Short Comings and Requirement of New Technique

Although the above give techniques do provide well enough VR support but this is highly constrained to good forecasted feeders. In case when the load has crossed it boundaries in terms of capacity the required Grid Code requirements [8] & [9] (see Fig 3) can't be obtained in a classic manner. Either the feeder line should be enhancing, in capacity or other technique must be employed to reduce the long power flows in the grid.

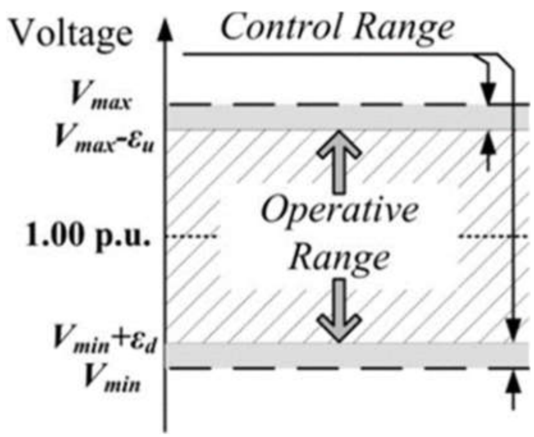

Fig 3 Grid Code requires Voltage should be in ± 0.95 p.u. range

2.3. Conventional Voltage Regulation Technique

Drops from Active Power flows are due to resistive nature of line, in classic paradigm these are catered through VR capability of OLTC-equipped Transformers [10-11]. On each node bus is connected a Distribution Transformer whenever there is an over or under-voltage the OLTC perform the VR by increasing/decreasing the number of taps. Drops due to reactive power compensation be realized through provision "Inertia". i.e., the provision of Reactive demand to the local load. Instead of Reactive demand being fed from the centralized source, the reactive demand is fed local by two ways: Passive Source- capacitor banks [12] tied before the reactive load center or by active equipment consisting of SVC [13], IVR [14], Synchronous Generators. Passive topologies are manually operated, while active ones automatically regulate their reactive power injection, so as to optimize their input to VR.

2.4. Smart Grid Approach

In SGs the generators, storage and loads are controllable and can offer VR by minimizing either PS losses (Optimal Power Flow - OPF) or the sum of standard deviation of bus voltages from nominal value (voltage profile optimization) [15-17]. Commonly used techniques of SG VR are by sensitivity analysis, Rule based control and P ∝ f and Q ∝ V methods. In [18], [19] and [20] Sensitivity Analysis, methodology for VR relies on; assessment of the voltage dependent derivatives of the inverse Jacobian matrix of the Newton Raphson power flow method. Rule-Based Control [21], [22] relies on schemes that drive the OLTC equipped T/Fs, so as to ensure that all bus voltages are in limits. P ∝ f and Q ∝ V [23], [24] used to design generic active/reactive power controller for DG units at distribution level; however, the R/X ratio may well affect the validity.

3. PROPOSED METHODOLOGY FOR VR SUPPORT

Similar to a re-dispatch-based approach followed by a VPP to provide VR dynamically [25], future static-injections may be designed for and applied on a weak grid to lower conventional inflows. Here the positions of the point mass for injections are found by optimizations for maximum loading and average loading of the weak feeder, which shall be shown to turn it considerably less lossy. The Horizon-Flow-Power flow technique as discussed in Sec-I to avoid long power flows from conventional follows the following Methodology:

3.1. Selection of Distribution Line/s

Shortlisting of feeders is done as a first step. Weak feeders are identified that includes MV & LV Lines and distribution transformers are often overloaded and losses very high which have the greatest number of technical losses. This can be done by investigating the recovery of sold units during a particular interval of time through Distribution Utility.

3.2. Identifying the Load Center/s

Voltage drops usually occur and originate at load centers. Load center are usually located at point where number of taps for distribution transformers are clustered [26–28]. Load Centers have a high demand of electricity. Poorly designed feeders may have load centers in between the source and final tap off or the very end of the feeder. Both cases will have high losses due to huge number of currents drawn.

To pursue this, following notions are proposed:

- Modeling connected loads as point-masses
- Modeling a center of Load-Mass (Locating an aggregate Load Center)

So, in mathematical form, we have,

$$g_L = \frac{\sum_{k=1}^{m}(P_{LK}\sum_{m=1}^{k} Z_m)}{\sum_{m=1}^{k} P_{LK}} \quad (1)$$

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Where g_L = Centre of Load –Mass (Ohms)
P_{LK} = Load connected at Node k (kVA)
$\sum_{m=1}^{k} Z_m$ = Accumulated Impedance till Node k (Ohms)

So that every node/ bus on the feeder is associated with an impedance and therefore Center of Load-Mass corresponds to a particular node.

3.3. Allocating the Point/s of DG Penetration

Positioning the DG source requires a great deal of planning involved. Factors such Area required for setup of DG Plant, Feasibility of setting up a RES based DG for the locality, Interconnection for Coupling DG to Distribution Grid, Hosting Capacity of Distribution Grid to incorporate the DG Units and locality of load centers as defined above, are all such factors need to addressed [29-30].
In a similar way proposed in Step-B, this is proposed by:

- Modeling Power Injections as point-masses
- Modeling a center of Injected-Mass (Locating an aggregate Penetration Center)

So that every node/ bus on the feeder is associated with an impedance and therefore Center of Injected-Mass corresponds to a particular node (of aggregated penetration).

3.4. Amount of Penetration Required

Finally, the sizing of DG unit at the allocated point is required. The size of the DG depends on the local demand of load center to be fed that usually causes huge long power flows. Sizing of DG also requires Hosting Capacity of the feeder [31-33]. This is modeled by:

- Minimizing position difference of load and injected power
- Minimizing IR (=Voltage Drop) losses corresponding to effective distance of power drawn by the aggregate load.

Mathematically this can be done, solving an optimization problem to minimize:
Position Difference: $g_L - g_G$ (2)
Area Under the Curve: $g_L \sum_{m=1}^{k}(P_{Lk}) - g_G \sum_{m=1}^{k}(P_{Gk})$ (3)
$g_L \sum_{m=1}^{k}(P_{Lk})$ = Accumulated Power Load (A.L.P)
$g_G \sum_{m=1}^{k}(P_{Gk})$ = Accumulated Injected Power (A.I.P)
A.L.P - A.I.P = Effective Depth of Power-flow

4. IMPLEMENTATION ON GOHWINDI FEEDER

For the purpose of implementing the proposed technique an MV (11kV) feeder is chosen, GOHWINDI feeder. The main body of the feeder consists of 93 nodes and 82 branches and is about 25 kilometers long.

Implementation is done in two major steps: First, Application of the proposed methodology to allocate & quantify the amount of Feeder DG Penetration. Second, the proposed penetration scheme is then fed into a simulation platform to simulate the voltage profile and power losses statutes before and after penetration.

The load simulation was done by means of the software package OpenDSS; a distribution system simulation program developed by EPRI (Electric Power Research Institute, CA, USA)

OpenDSS is an electric power distribution system simulator (DSS) which is used for studying power analysis at distribution level primarily and is a useful tool for grid integration and grid modernization. It enables engineers to

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perform complex analyses specifically to meet current and future distribution system challenges and provides a foundation for understanding and integrating new technologies and resources. The environment is not based in GUI rather it's more like a coding environment but due to large analysis capability, this is much better than other paid analysis tools like PSS/E. The purpose of this simulation tool is to analysis the systems at more on distribution level.

During the designing of this particular feeder, real time input data was arranged from *Lahore Electric Supply Company* (LESCO) which is one of major distribution company of Pakistan. The following data was obtained from LESCO and was used for the simulations along with some assumptions:

- The hourly load profile of the feeder for the whole year 2018/19
- Conductor type and length of all sections of the system (.kmz file)
- The height of the distribution poles (.kmz file)
- The rating of all distribution transformers (.kmz file)
- The geographical position of lines and transformers, represented by x, y coordinates (.kmz file)
- Load shapes are constant during simulations

Besides this data, several assumptions were made to perform this analysis.

- The load distribution has been assumed to be proportional to the rating, i.e., the according hourly feeder load has been divided to the transformers by their share of the total transformer capacity. This assumption is acceptable; even small differences would not affect the overall results too much.
- For the line geometry, a typical conductor distance of 1.5 ft was assumed as the industry standard (which is needed for the simulation).
- Voltage regulation in the substation was assumed to be present for regulating between 11 and 11.5 kV, according to the load. This means that for higher loads, a voltage drop along the line is already anticipated and compensated by slightly increasing the starting voltage. This is a common practice and commonly used across most substations in Pakistan (and the world). This does not have a positive effect of decentralized PV solar, but should be considered in order to be realistic.
- The power factor of the load has been assumed constant at 0.8 which was taken as the average from the readings of primary terminals of the distribution transformers.

Some of data has been taken from other sources. The irradiance data of the year is taken from a PVSyst report. The maximum permissible currents of the conductors (per phase) have been taken from manufacturer datasheets. The conductors which have been used in this feeder are *Dog, Rabbit* and Osprey whose maximum current carrying capacities are *312A, 197A* and *130A* respectively. Out of the data output from the simulation, two types of analysis have been elaborated for each of the different cases:

- **Static Analysis**: For one specific time point and load situation, the impact on (punctual) line losses and voltage levels along the different line branches has been assessed.
- **Annual Analysis**: The simulation is done for 24h time period, the simulation across a full year is time-consuming. Here we would like the readers to keep one thing in view that OpenDSS cannot perform Time Series Analysis and individuals run simulations for each specific time by themselves. Therefore, for arriving at annual average values, typical 24h time periods have been simulated for 3 different months of the year. The results of these have been extrapolated in order to derive annual average and total values for line losses and voltage levels along the line.

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Before, considering & determining the penetration criteria as per the proposed technique methodology, we have considered cases of maximum load, minimum load and average load simulations for static analysis for Only grid, 1MWp PV plus grid and 3 MWp PV plus grid. The value of maximum load *(6MW)*, minimum load *(1.2MW)* and average load *(2MW)* are obtained from *LESCO's* data.

4.1. Case A: Only Grid For Maximum Load (6 MW)

The 6MW load is most is most extreme case of year and it is not frequent but still for simulation point of view and grid stability concerns, we have performed simulations for this load. The feeder shared by LESCO is *GOHWINDI* feeder which can be seen in Figure 1. The details of this feeder are given in Table 1.

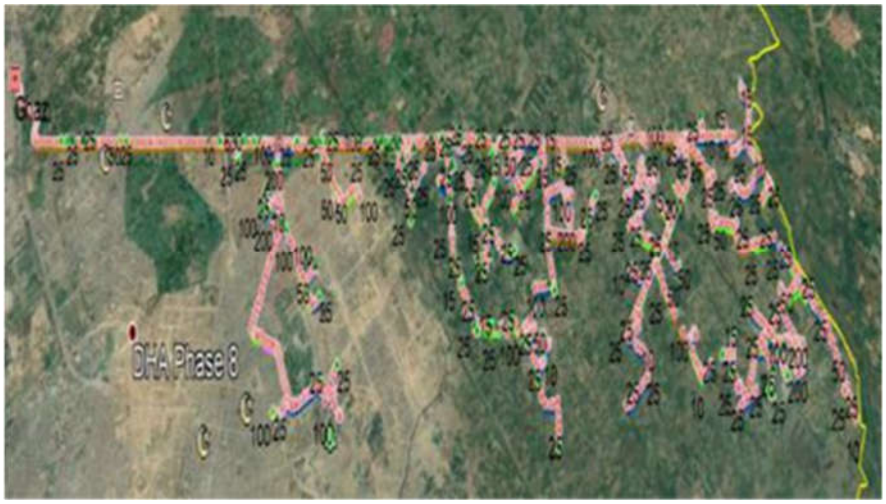

Fig 4 FEEDER

Table 1 FEEDER Details

Size of the Transformer	No. of Transformers Deployed
10	28
15	22
25	202
50	45
100	46
200	10
630	1

An exact model of this feeder is modeled and is shown in Fig 5 Modeling of the feeder is most time-consuming part of analysis and if things are not modeled in a aright way, then this may result in wrong results.

Fig 5 FEEDER Modeled in OpenDSS

Loading of feeder is shown in Fig 6. The thick line shows that line is densely loaded and thinner lines show less power delivery. It can be observed that branches have less power as the centered line as more branches are connected with a sub-branch, less power is delivered. This is also due to fact that after designing a feeder in past, instead of installing and setting new sub-stations and feeders, the previous lines are overloaded without catering and performing proper analysis.

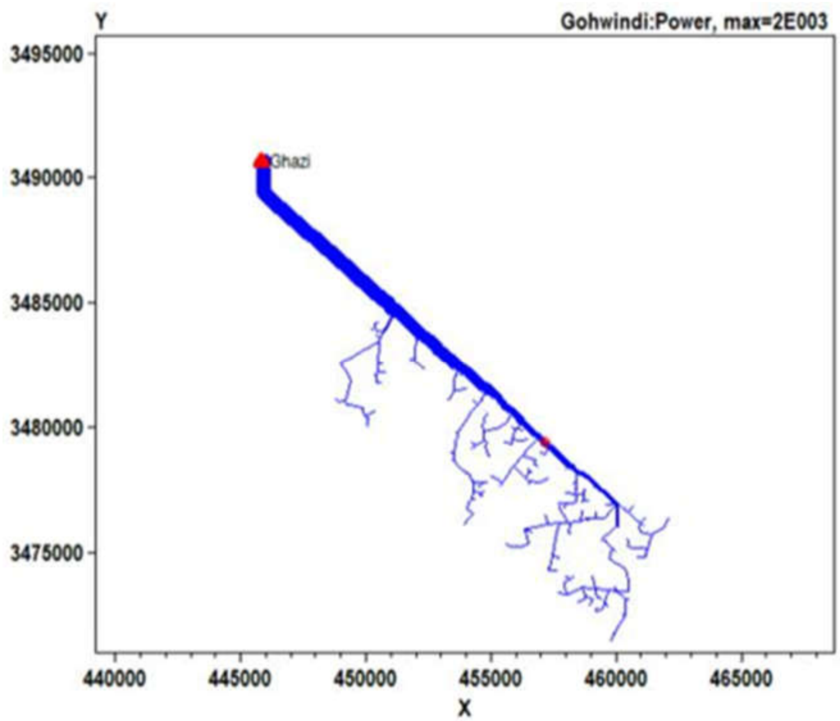

Fig 6 Power flow in FEEDER

Per unit voltage profile is shown in 11 kV has been assigned as value of 1.00 p.u. The allowed limit is 0.9 p.u. to 1.1 p.u. Three colors *Red, Blue and Black* correspond to 3 different phases. There can be observed a slight imbalance, but it is just minute, and it does not have any affect results and can be ignored. It should be kept in mind that for high voltage drop, high current will be dissipated and it means more power losses in circuit. It can be clearly seen that voltages at this maximum-load situation are well below the lower limit of allowable voltage for all places which are further than 5km away from the substation and these are all transformers in this case. The drop of voltage *MV* side of distribution transformer which is *11 kV* here results in same proportional voltage drop on *LV* side of distribution transformer which is *400 V* in our case.

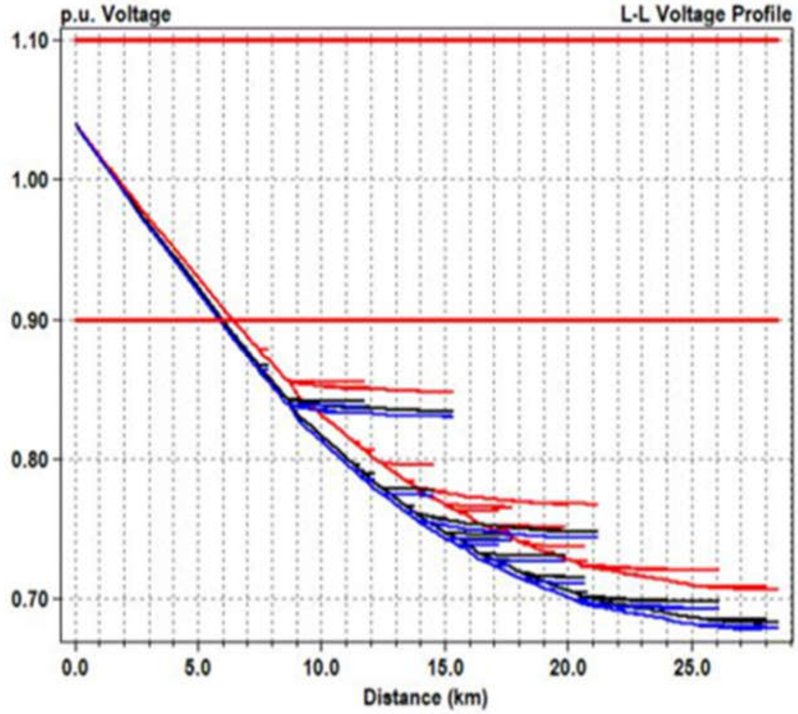

Fig 7 Voltage Profile

Fig 8 shows the GIS plot of line voltages: Green lines show voltage within limits and red lines show voltage below the lower limit (-10%). Lines beyond 5 km are below permissible limit here.

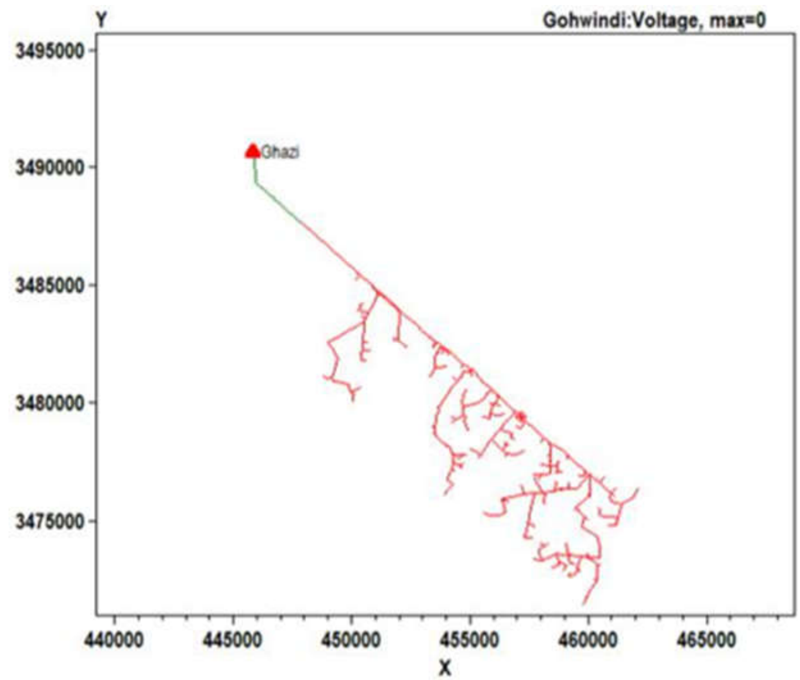

Fig 8 Voltage Flow in FEEDER

Table 2 shows the resulting load and loss values for this case. The total supplied power is about 6 MW, while the accumulated consumer load power is 4.7 MW. The line losses are therefore 1.3 MW or 29%.

Table 2 Loss Calculation

Loss Calculation	
Total Power	6050 kW
Total Load Power	4702 kW
Total Line Losses	1348 kW
Percentage Loss of Circuit	28.66 %

4.2. Case A: Average Summer Load (3 MW)

Fig 9 shows the simulation result for average summer load. The total load (line thickness) is less than for the maximum-load scenario and the resulting voltages of about half of the lines are within the limits in this case – considering the voltage control to 1.04 at the substation.

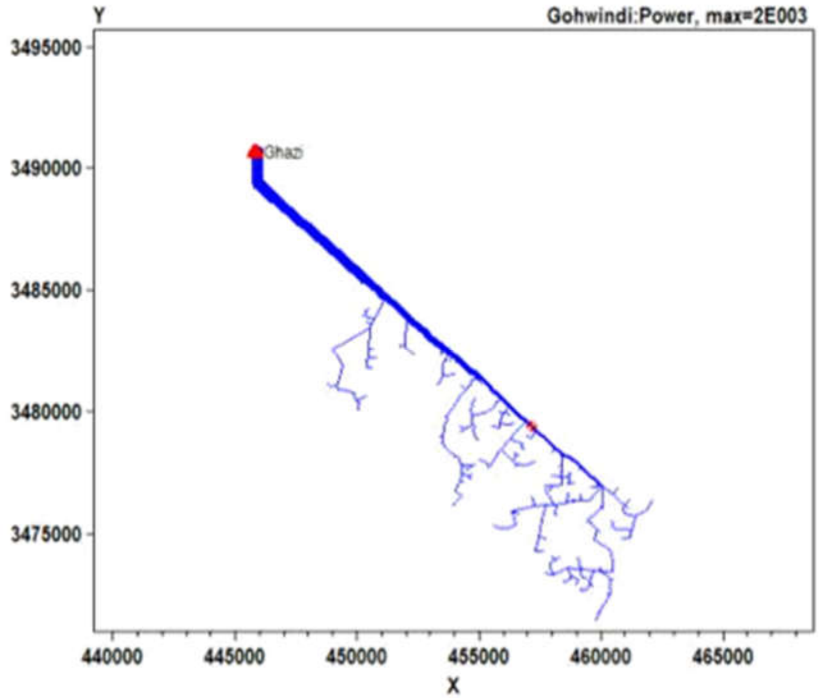

Fig 9 Power flow in FEEDER at an average load of 3 MW

Fig 10 shows the line voltage situation geographically: Here it can be observed, that in terms of transformers (equal to singular line ends), still more than half of the transformers suffer from low voltage in this case. Similarly, Figure 8 shows voltage profile. It is evident from Figure 8 that voltages are somewhat stable before 15 km from sub-station while going away, voltages drop.

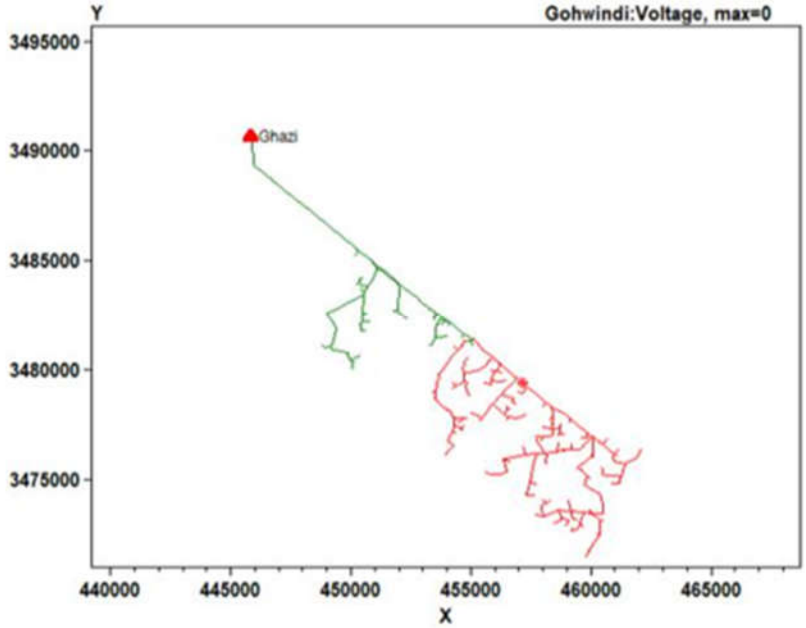

Fig 10 Voltage Flow

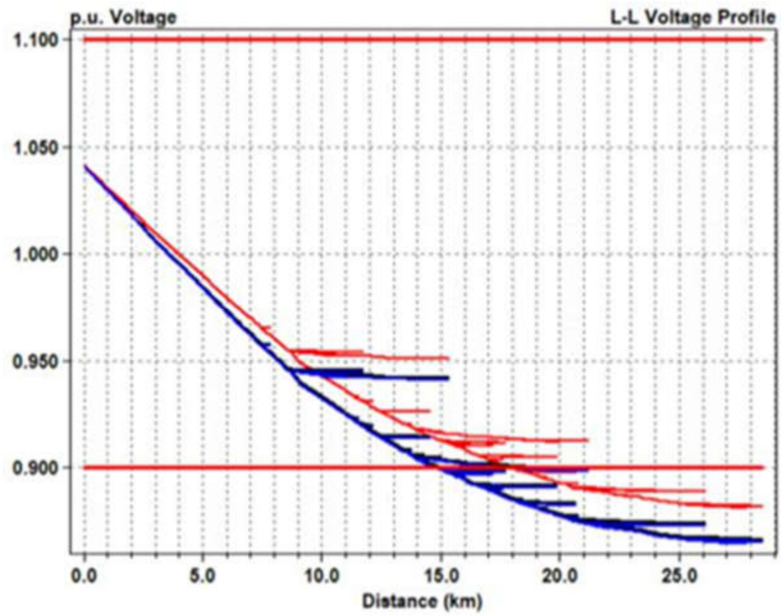

Fig 11 Voltage Profile

Table 3 shows the resulting load and loss values for this case. The total supplied power is about 3.1 MW, while the accumulated consumer load power is 2.8 MW. The line losses are therefore 0.3 MW or 12%.

Table 3 Loss Calculations

Loss Calculation	
Total Power	3081.9 kW
Total Load Power	2758.8 kW
Total Line Losses	323.1 kW
Percentage Loss of Circuit	11.71

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4.3. Case A: Minimum Load (1.2 MW)

Fig 12 shows the result of the situation at the minimum load situation: The total load (line thickness) is very little here from the start and the resulting voltages are within limits in this case along all of the line. In the same way Fig 13 and Fig 14 shows voltage profile and voltage flow in feeder. The loss calculation is given in Table 3.

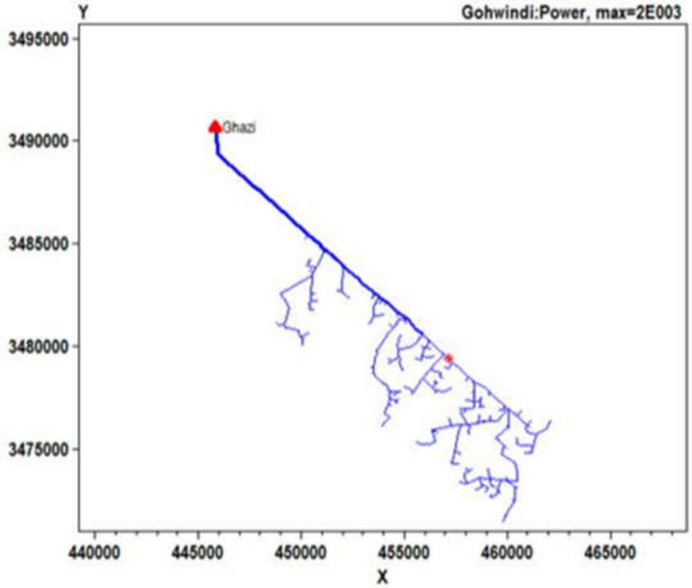

Fig 12 Power Flow

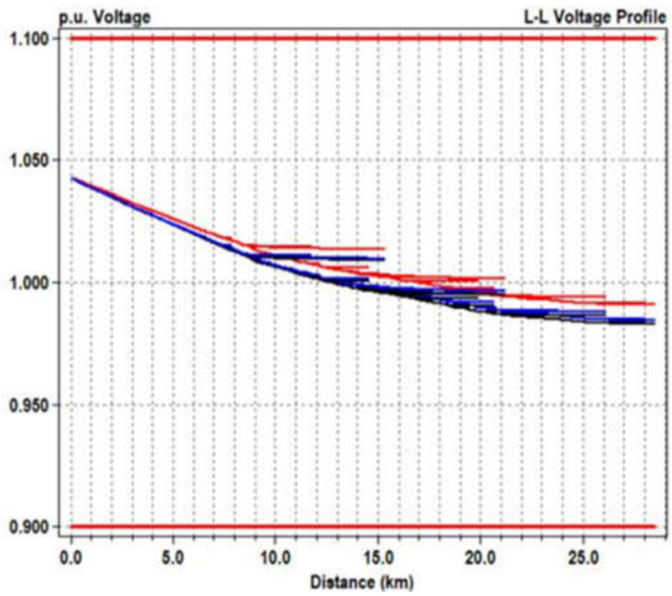

Fig 13 Voltage Profile

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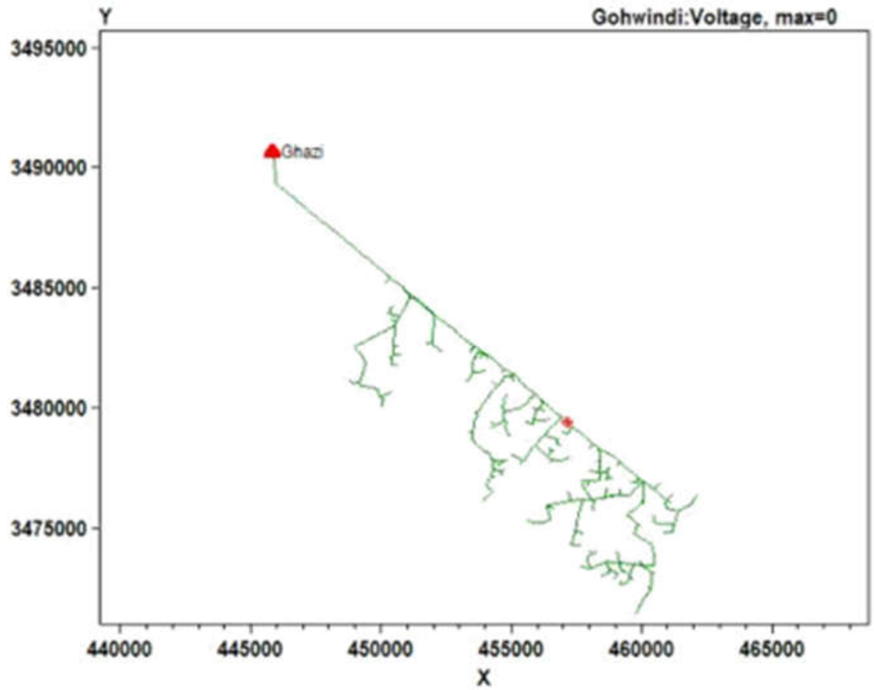

Fig 14 Voltage Flow

4.4. Case B: 1 MWp PV Injection Plus Grid For Maximum Load

1MWp of solar PV is installed towards end of the line and considered for this simulation at its maximum output of 0.8 MW (i.e., around noon, while during 2 hours before and after that, the output would be similar, i.e. of 0.7 to 0.8 MW).

Center line is still loaded with significant power (about 5.2 MW as PV is giving in 0.8 MW here). Voltages are now improved, but only slightly. In the "grid-only" case, the voltage at the end of the line was below 0.70 p.u., while in this case, it is above 0.70 p.u. Following figures represent the power flow, voltage profile and voltage flow.

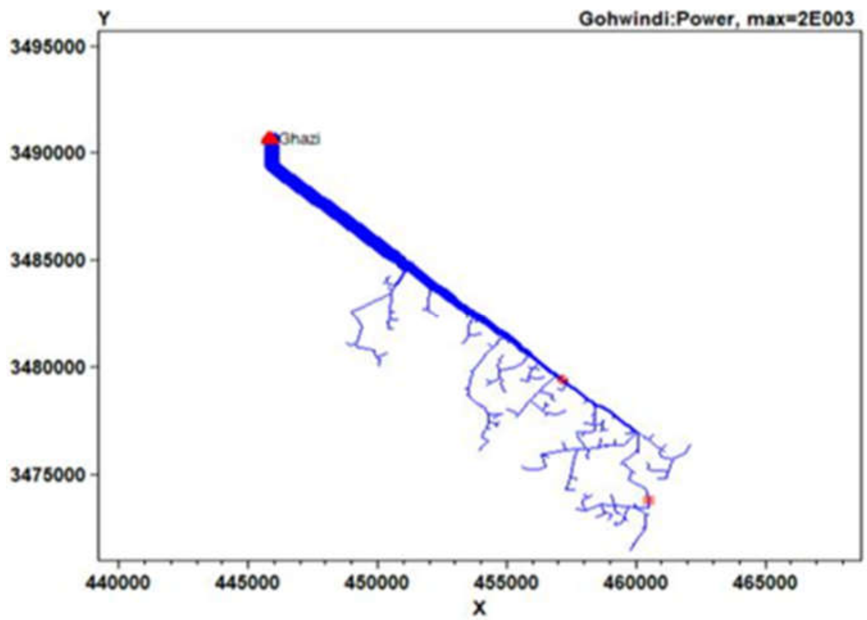

Fig 15 Power Flow

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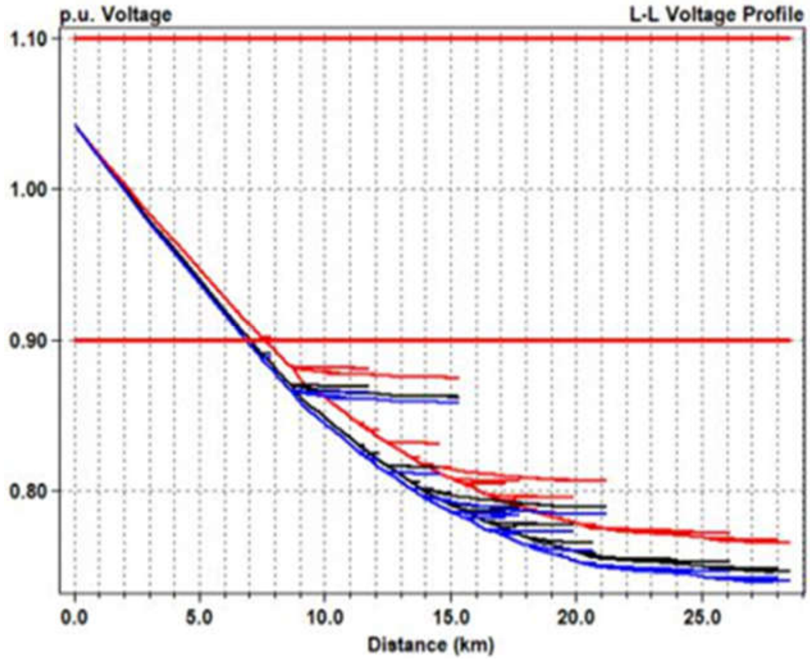

Fig 16 Voltage Profile

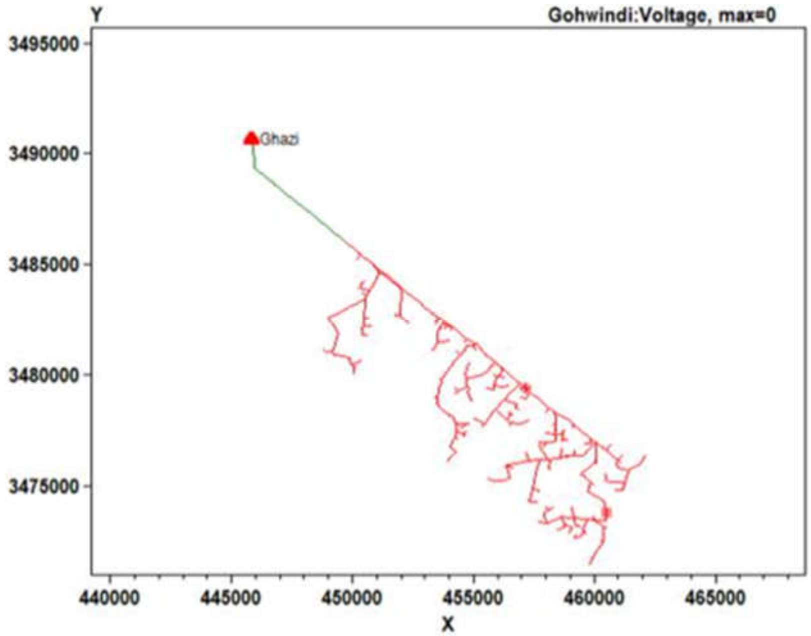

Fig 17 Voltage Flow

Table 4 Loss Calculation

Loss Calculation	
Total Power	5682.2 kW
Total Load Power	4704.5 kW
Total Line Losses	978.3 kW
Percentage Loss of Circuit	20.79 %

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The effects on total numbers can be seen in Table 4. The line losses are decreased from about 1.35 to about 1.0 MW or 29 to 20.8% which is also reflected in the "Total Power", which is correspondingly reduced.

4.5. Case B: Medium Load (3 MW)

In the case of low load, the voltage and losses were already acceptable without PV. With 1MWp of PV, voltage levels are even more constant now across the line, but the positive effect is less significant than before. Fig 18, represents power flow, Fig 19 voltage profile and Fig 20 the voltage flow.

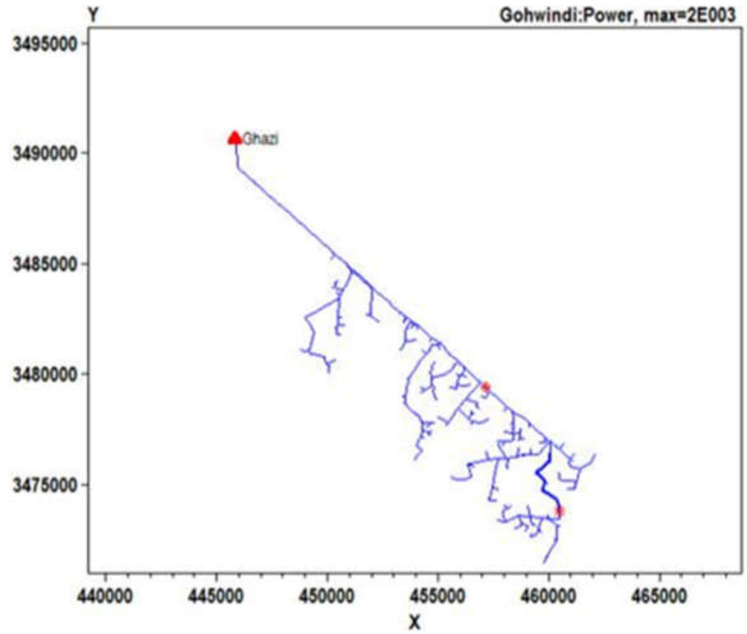

Fig 18 Power Flow

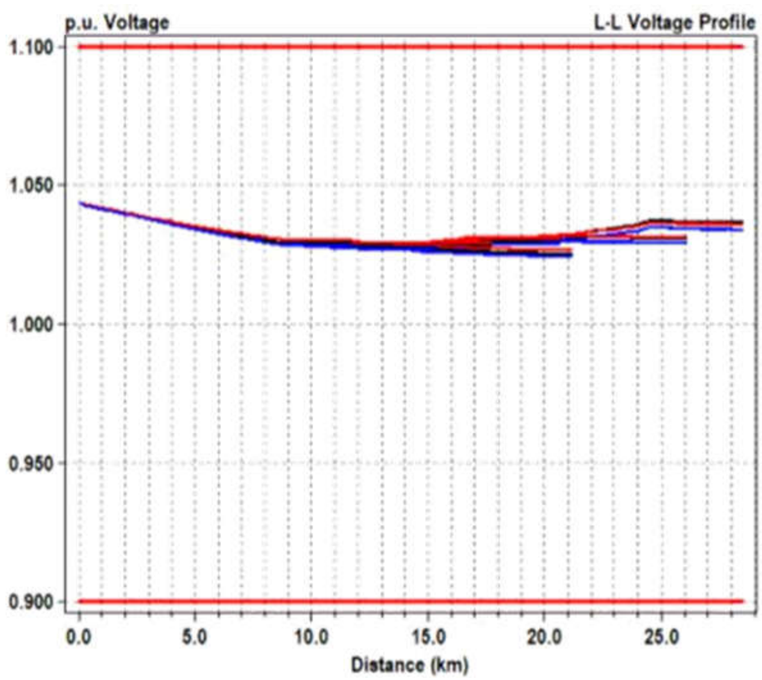

Fig 19 Voltage Profile

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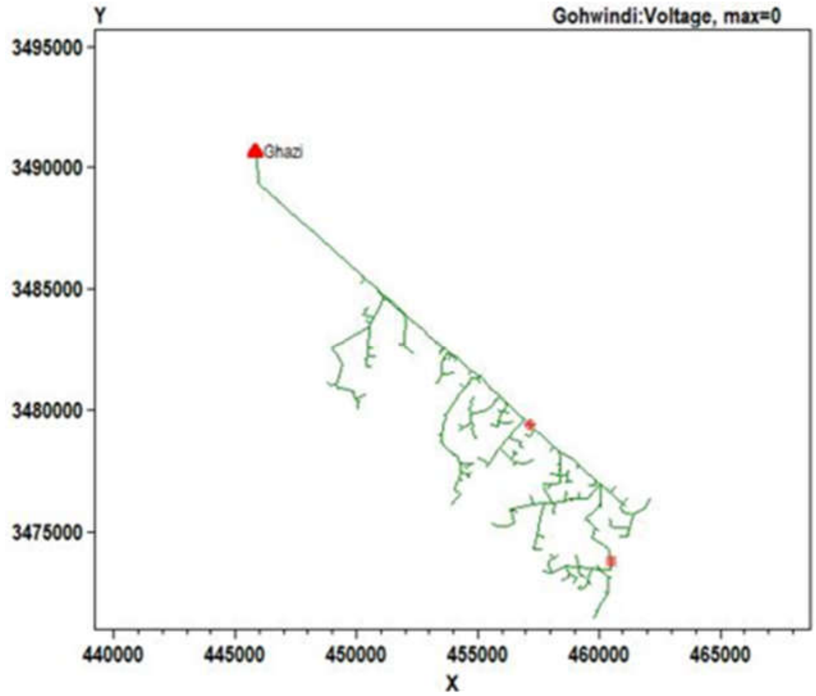

Fig 20 Voltage Flow

The line losses are decreased from about 44 to about 12 kW or 3.6% to 1%, which is an improvement, but much less significant than for higher load situations.

Table 5 Loss Calculation

Loss Calculation	
Total Power	1223.3 kW
Total Load Power	1211.2 kW
Total Line Losses	12.1 kW
Percentage Loss of Circuit	1.00 %

4.6. Case B: Minimum Load (1.2 MW)

In the case of low load, the voltage and losses were already acceptable without PV. With 1MWp of PV, voltage levels are even more constant now across the line, but the positive effect is less significant than before. Figures below depicts power flow, voltage profile, voltage flow. The line losses are decreased from about 44 to about 12 kW or 3.6% to 1%, which is an improvement, but much less significant than for higher load situations.

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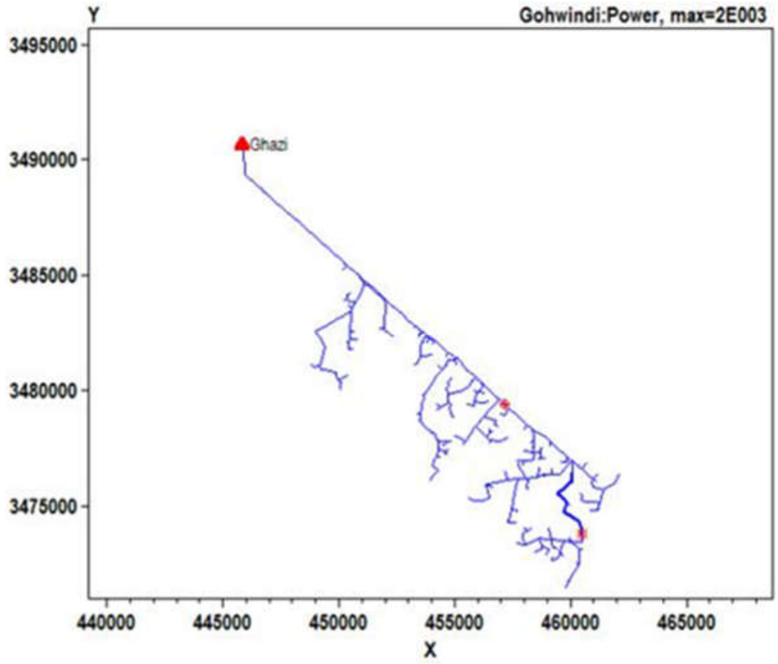

Fig 21 Power Flow

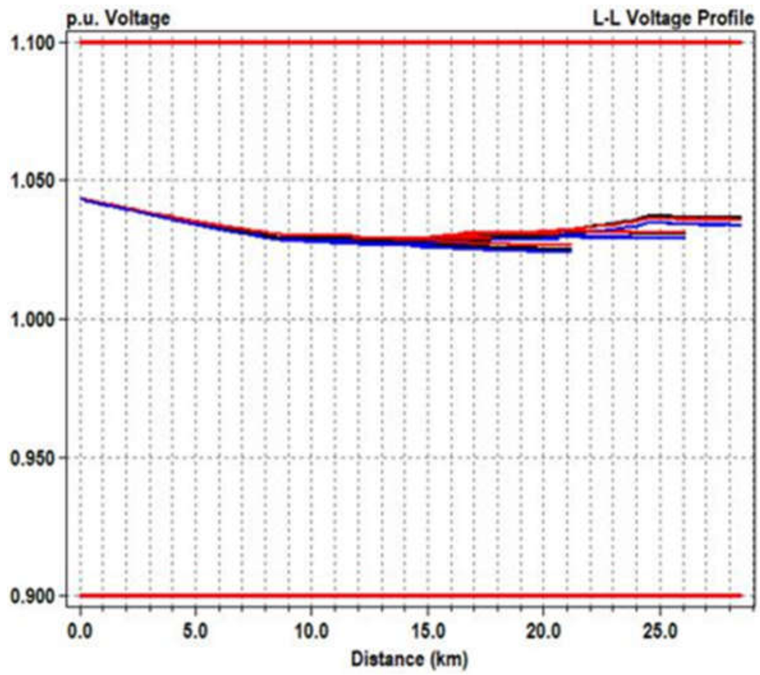

Fig 22 Voltage Profile

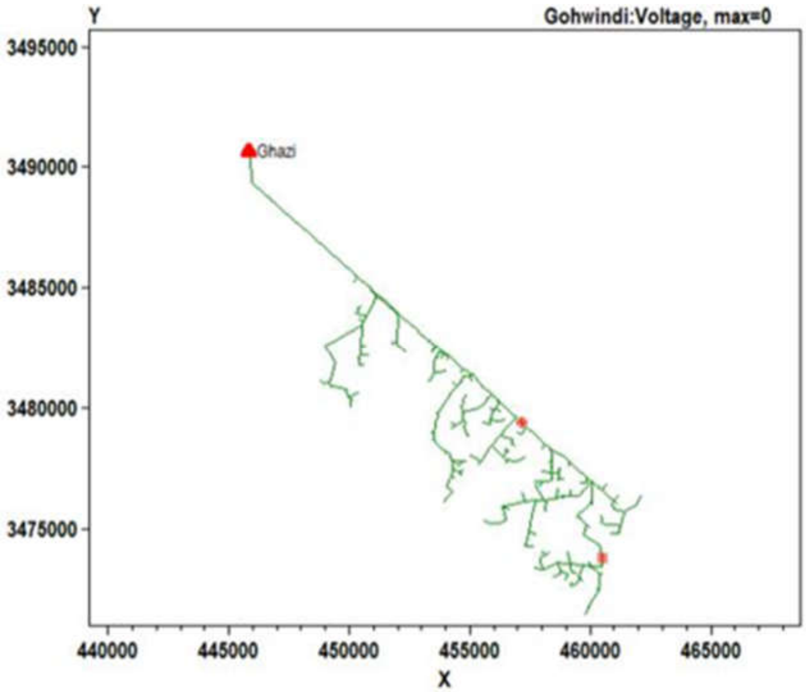

Fig 23 Voltage Flow

Table 6 Loss Calculation

Loss Calculation	
Total Power	1223.3 kW
Total Load Power	1211.2 kW
Total Line Losses	12.1 kW
Percentage Loss of Circuit	1.00 %

4.7. Case C: 3 MWp PV Power Plant With Grid For Maximum Load

3 MWp PV is inserted with size of 1 MWp plants at different load locations. The maximum output from each at noon is 0.8 MW AC power.

Compared to the 1 MWp PV case, the main line is now significantly improved of its burden and carries only about 3.6 MW instead of 6 MW without PV. Voltages are now drastically improved and maintained within their limits of above 0.9 p.u., while without PV, they dropped below 0.7 p.u. at the line end. Figures below depicts power flow, voltage profile, voltage flow.

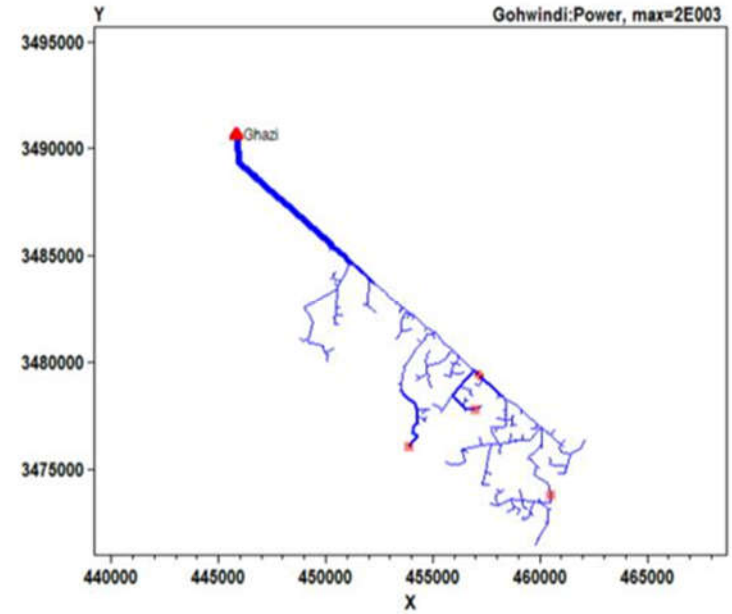

Fig 24 Power Flow

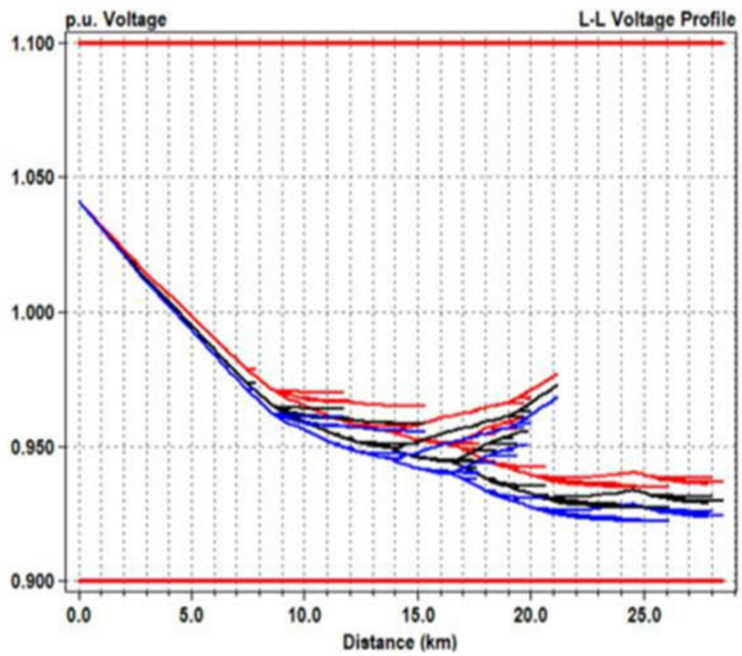

Fig 25 Voltage Profile

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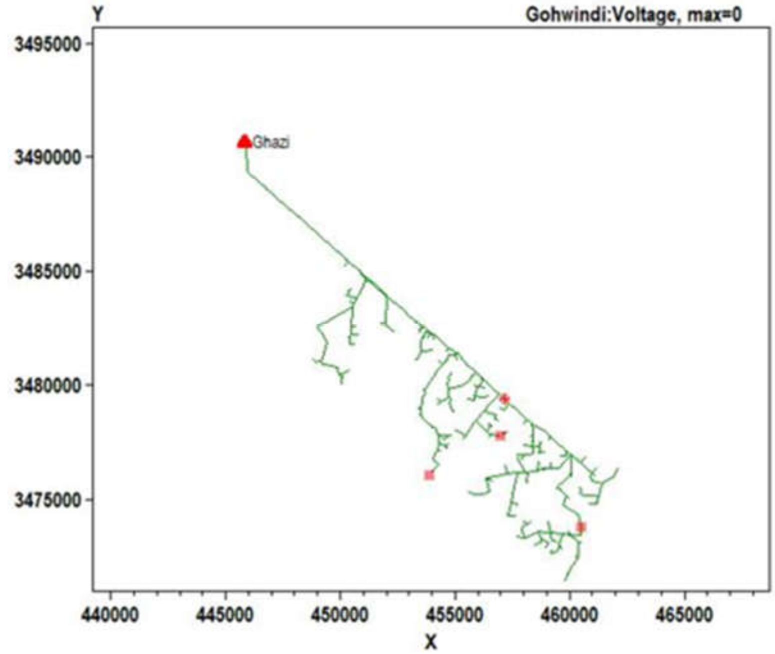

Fig 26 Voltage Flow

The effects on total numbers can be seen. The line losses are decreased drastically from about 1.35 to about 0.2 MW or 29 to 4% – which is also reflected in the "total power", which is correspondingly reduced from 6 MW to 5 MW.

Table 7 Loss Calculation

Loss Calculation	
Total Power	4958.3 kW
Total Load Power	4764.9 kW
Total Line Losses	193.4 kW
Percentage Loss of Circuit	4.06 %

4.8. Case C: Average Load 3MW

3 MWp of PV under the average load situation, voltage results are same. All lines are now within the limits and much better profile than 1 MWp. Figures below depicts power flow, voltage profile, voltage flow.

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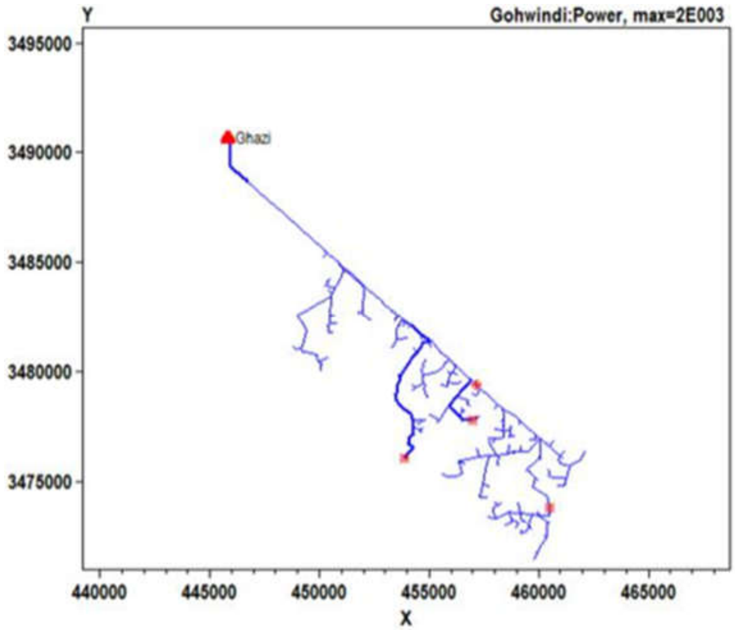

Fig 27 Power Flow

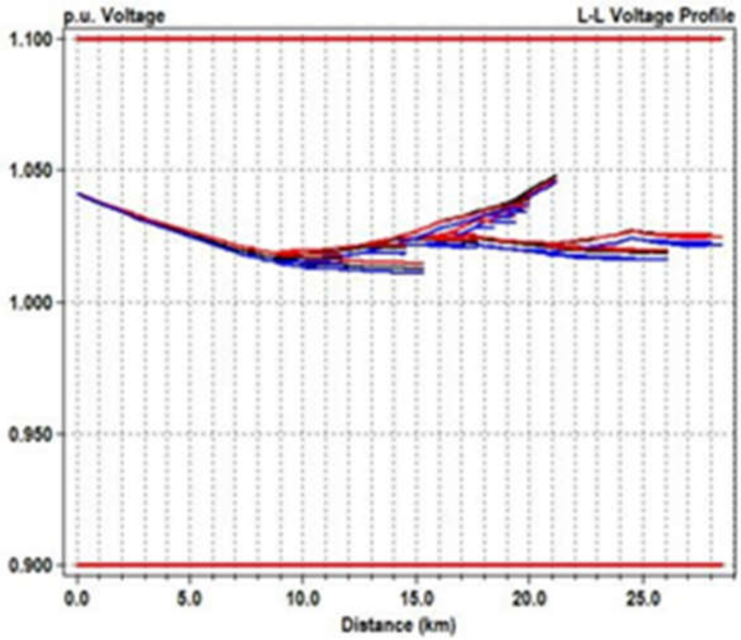

Fig 28 Voltage Profile

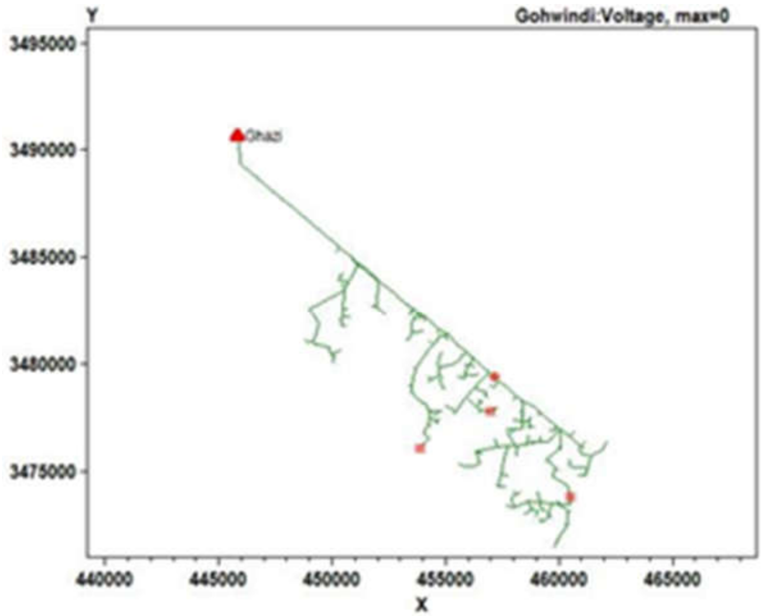

Fig 29 Voltage Flow

Table 8 Loss Calculation

Loss Calculation	
Total Power	3440.6 kW
Total Load Power	3391.4 kW
Total Line Losses	49.2 kW
Percentage Loss of Circuit	1.45 %

4.9. Case C: Minimum Load (1.25 MW)

In the case of minimum load and maximum output of 3 MWp solar, the possible adverse effects of high decentralized feed-in can be observed: Due to the high feed-in toward the end of the line, the voltage levels are increased such that the voltage exceed its upper limits in this case at some places. However, this assumes a static constant voltage regulation as the substation level. Without this, the upper voltage level would not be more than its limit.

Compared to the 1 MWp case, line losses are actually now increased again from 1% to 4%. This is due to the relatively long distance between PV plants and substation which the exported power has to travel and it is not the loss of power plant power in line. Figures below shows power flow, voltage profile, voltage flow.

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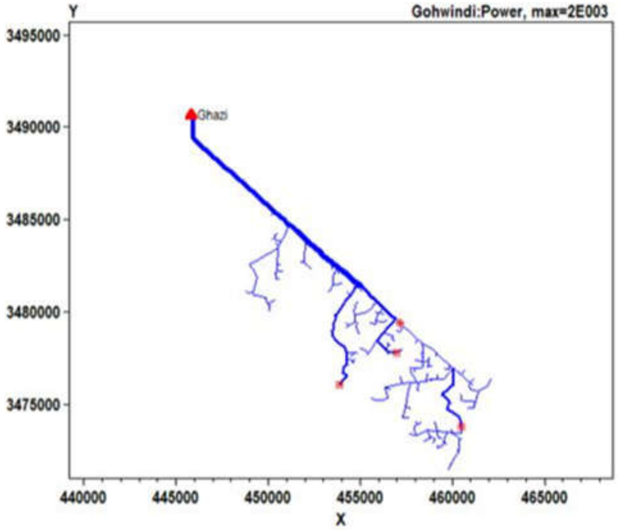

Fig 30 Power Flow

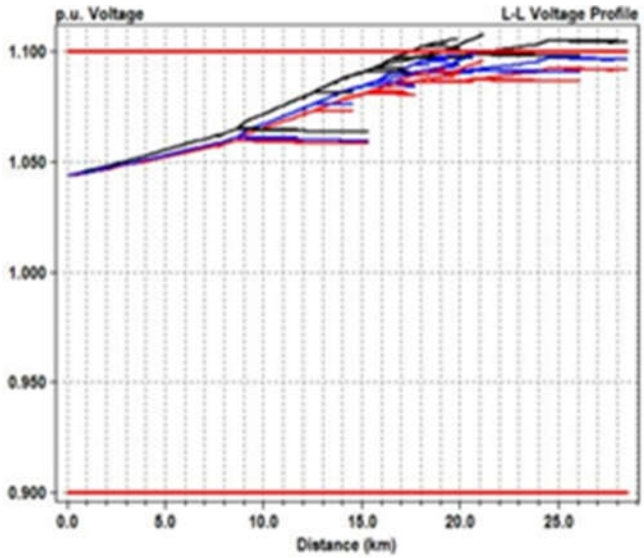

Fig 31 Voltage Profile

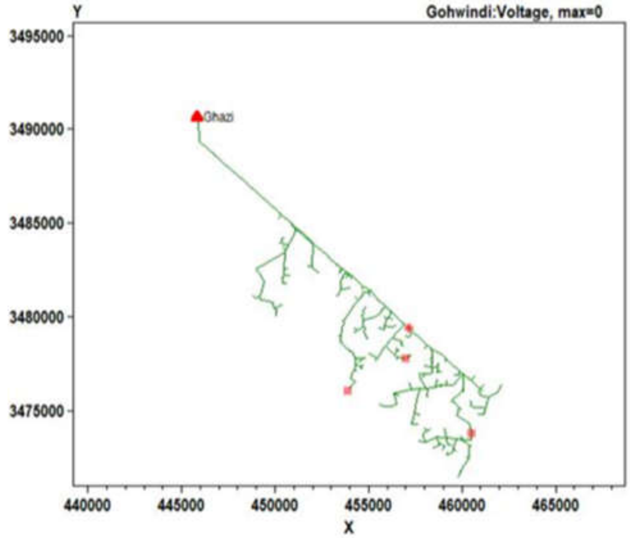

Fig 32 Voltage Flow

 doi:10.20944/preprints202204.0275.v1

Table 9 Loss Calculation

Loss Calculation	
Total Power	1390.7 kW
Total Load Power	1259.6 kW
Total Line Losses	131.1 kW
Percentage Loss of Circuit	10.40 %

The Table 10 below gives an overview of loss calculations in all these scenarios.

Table 10 Summary Table

Load category	Case	Loss %
Maximum Load 6MW	Grid Only	28.66 %
	1MWp PV	20.79%
	3MWp PV	4.06%
Medium Load 3MWp	Grid Only	11.71%
	1MWp PV	6.04%
	3MWp PV	1.45%
Minimum Load 1.2 MWp	Grid Only	3.61%
	1MWp PV	1.00%
	3MWp PV	10.40%

4.10. Yearly Analysis

As mentioned earlier that OpenDSS cannot perform time series analysis. It is a time-consuming process and may take several months and very high precision to perform accurately. However, we have performed simulation for the days when maximum load and minimum load was observed. Similarly, for average load this simulation is performed for one day. Please keep in mind that irradiance value which was obtained from PVSyst are also converted into p.u system with using 1020 W/m^2 as base.

4.11. Penetration Criteria

Penetration criteria for a maximum of 6MW feeder loading was done. Calculation is as followed.

On application following is Point- Mass Load Profile:

g_G = 4.715 Ohms ……... (Center of Load Mass)

$\sum_{m=1}^{k}(P_{Lk})$ = 6000 kVA…... (FEEDER Loading)

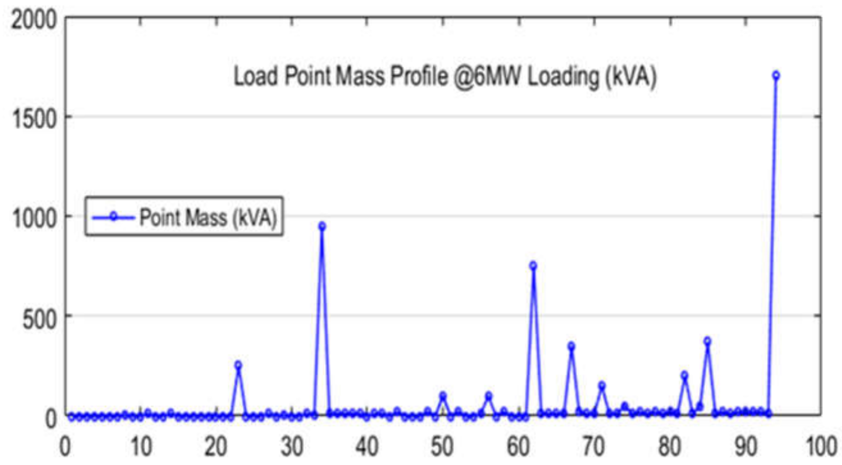

Fig 33 Load Point Mass Profile at 6 MVA loading

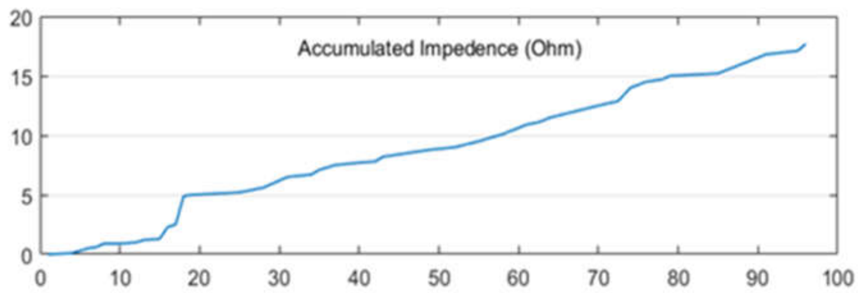

Fig 34 Accumulated Impedance in Ohms

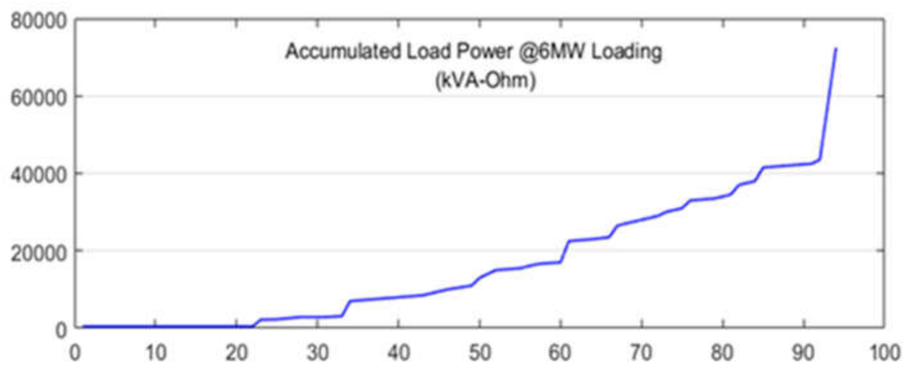

Fig 35 Accumulated Load Power at 6 MW Loading

Optimal Injection of DG Power is optimized by minimizing the described constrains by following methods:

4.11.1. Hit & Trial Method

In this method, DG power was randomly placed by judging the position of cluster of loads and position of Center of Injects and thereby minimizing the Position Difference ($\mathbf{g}_L - \mathbf{g}_G$) and also corresponding the voltage drops by minimizing area under the Effective Depth of Power-flow (A.L.P - A.I.P) curve. This is illustrated as under:

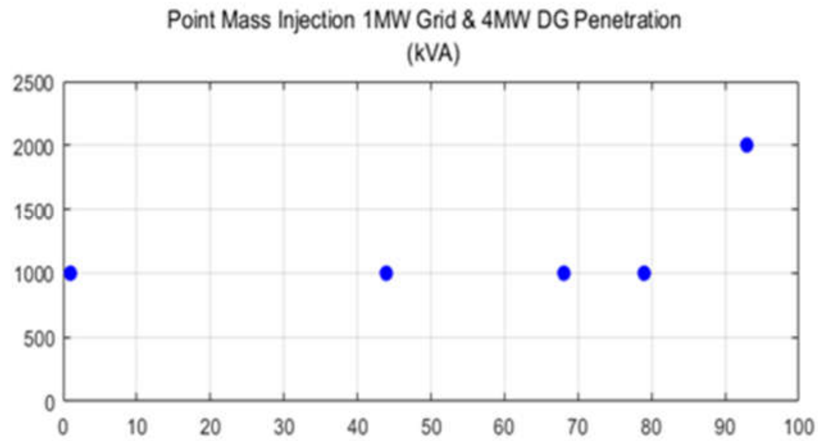

Fig 36 Point Mass Injection in 1MW Grid and 4MW DG Penetration

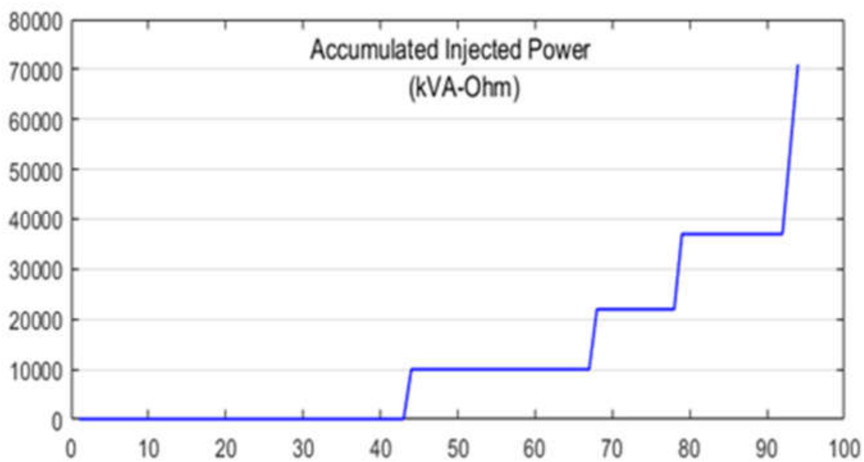

Fig 37 Accumulated Injected Power (kVA-Ohms)

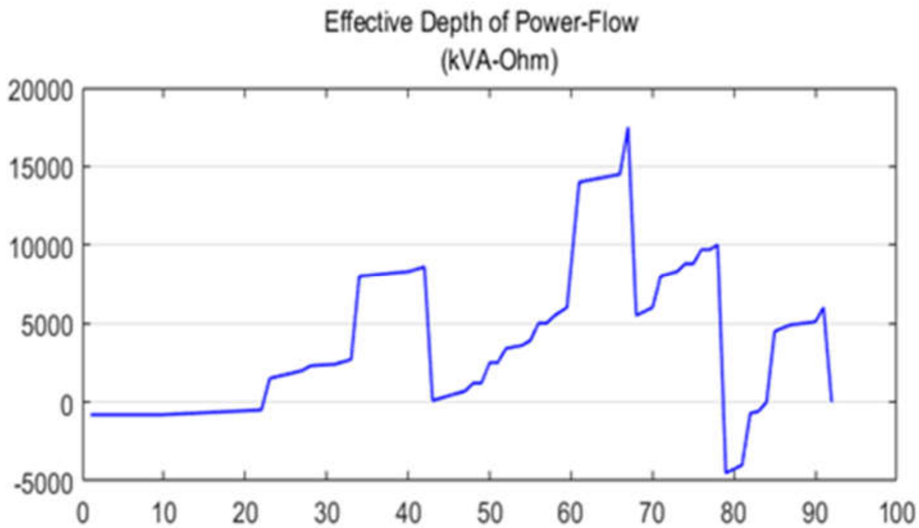

Fig 38 Effective Depth of Power Flow

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4.11.2. Optimization Method

In this method, DG power was optimally placed by optimization tool of Excel, 'Solver' Add-in by minimizing distance between Load Center & Center of Injections through some constraints of limited total injection and grid feed-in. This is illustrated as below:

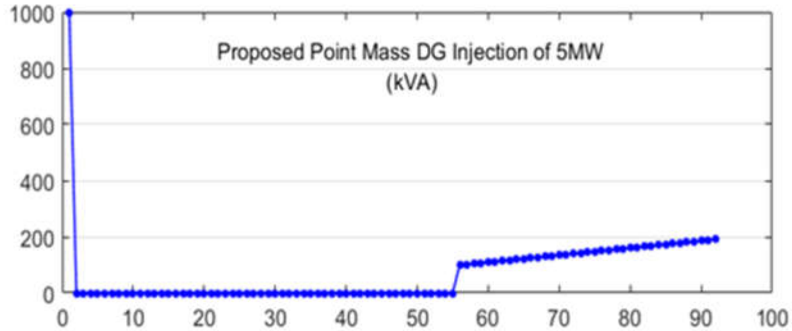

Fig 39 Point Mass DG Injection of 5 MW

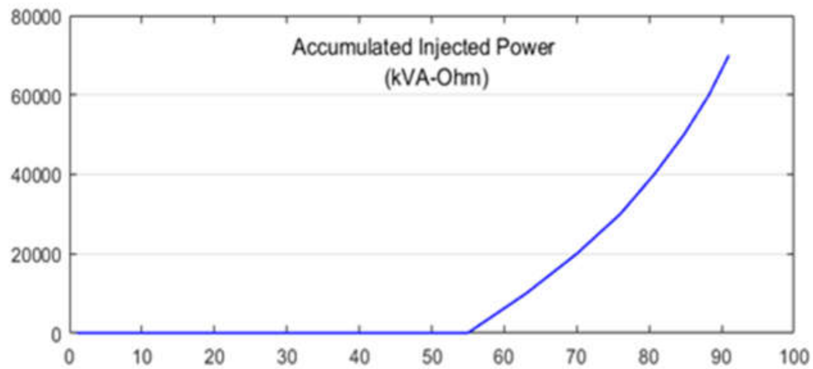

Fig 40 Accumulated Injected Power at 5MW Loading

Here we can clearly visualize how DG Injections have improved voltage profile of the feeder. Some of the results of the penetration criteria simulation are given as follows:

Table 11 Points of DG Injections

Points of DG Injection	6000	5000	4	39

4.12. Application of Penetration Critreria on OpenDSS

The proposed penetration criteria as evaluated above is now fed in to the simulation tool for the modelled feeder on corresponding node and following are the results which are obtained. Following figures represent the penetration of 3 MWp PV and 2 MW of batteries to support our grid. It can be observed by voltage profile, voltage flow and power flow of PVs and storage case doesn't improve that much but just provide more grid reliability.

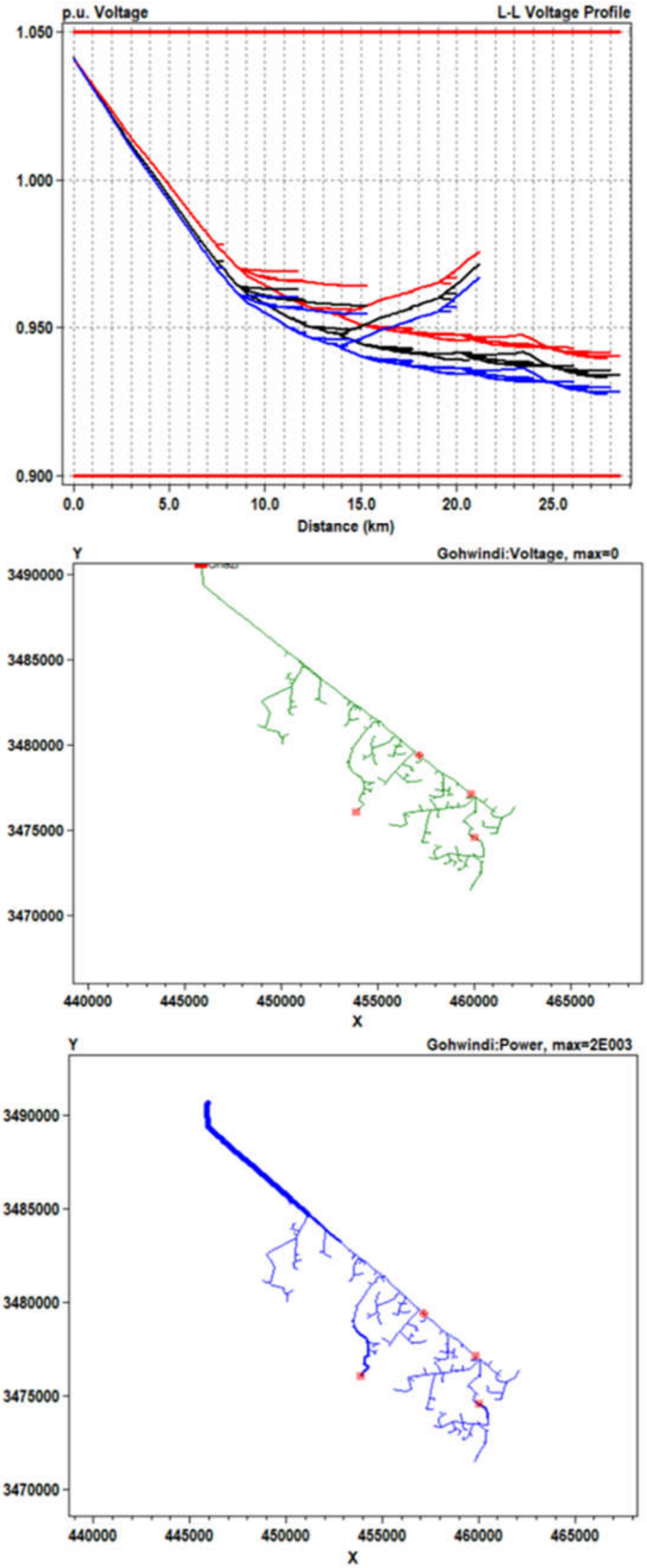

Fig 41 Voltage Profile, Voltage Flow and Power Flow

The below table represents the loss calculations.

Table 12 Loss Calculations

Loss Calculation	
Total Power	1390.7 kW
Total Load Power	1259.6 kW
Total Line Losses	131.1 kW
Percentage Loss of Circuit	10.40 %

5. CONCLUSION

From the implementation of the proposed technique to a real-time weak feeder on a purely conventional grid has shown incredible results as penetration of distributed sources have clearly reduces long-power-flow, by replacing local demand with horizontal flows for neighboring points of penetrations on the feeder. Future studies on Payment model for technique for ancillary service can be done and corresponding business model could be proposed for public and private investors. This study focuses on provision of active power from DG sources, similar model could be proposed for reactive sources with may replace slower conventional equipment for VR like capacitor banks and SVCs. It is also conceivable that businesses might be setup for the sole purpose of selling reactive support or voltage control. Studies could further be done if this technique was replicated on a smaller yet multiple scale for multiple rooftop solar in metropolitan area feeders. With rise in other RES sources like wind power, micro hydro, microchips, large storages, EVs and other DGs could aggregate their supplies to make a Virtual Power Plant that has a highly controlled dispatch mechanism to provide ancillary support. Studies could be done on mere hosting capacities of Distribution feeder for voltage support.

Acknowledgement

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References

1. Di Fazio, A.R., Fusco, G. and Russo, M., 2013. Decentralized control of distributed generation for voltage profile optimization in smart feeders. *IEEE Transactions on Smart Grid*, *4*(3), pp.1586-1596.

2. Vovos, P.N., Kiprakis, A.E., Wallace, A.R. and Harrison, G.P., 2007. Centralized and distributed voltage control: Impact on distributed generation penetration. *IEEE Transactions on power systems*, *22*(1), pp.476-483.

3. Kim, S.B. and Song, S.H., 2020. A hybrid reactive power control method of distributed generation to mitigate voltage rise in low-voltage grid. *Energies*, *13*(8), p.2078.

4. Souza Junior, M.E.T. and Freitas, L.C.G., 2022. Power Electronics for Modern Sustainable Power Systems: Distributed Generation, Microgrids and Smart Grids—A Review. Sustainability, 14(6), p.3597.

5. Irfan, M., Zhao, Z.Y., Ahmad, M. and Rehman, A., 2019. A techno-economic analysis of off-grid solar PV system: A case study for Punjab Province in Pakistan. Processes, 7(10), p.708.

6. Nadeem, A., Rossi, M., Corradi, E., Jin, L., Comodi, G. and Sheikh, N.A., 2022. Energy-Environmental Planning of Electric Vehicles (EVs): A Case Study of the National Energy System of Pakistan. Energies, 15(9), p.3054.

7. Yang, H., Zhang, Z., Gao, J., Xun, T. and Li, S., 2022. A Repetitive Low Impedance High Power Microwave Driver. *Electronics*, *11*(5), p.784.

8. Alves, M.F. and Ribeiro, T.N., 1999, April. Voltage sag: an overview of IEC and IEEE standards and application criteria. In *1999 IEEE Transmission and Distribution Conference (Cat. No. 99CH36333)* (Vol. 2, pp. 585-589). IEEE.

9. Von Jouanne, A. and Banerjee, B., 2001. Assessment of voltage unbalance. *IEEE transactions on power delivery*, *16*(4), pp.782-790.

10. Srećković, N., Rošer, M. and Štumberger, G., 2021. Utilization of Active Distribution Network Elements for Optimization of a Distribution Network Operation. *Energies*, *14*(12), p.3494.

11. Schultis, D.L. and Ilo, A., 2021. Effect of Individual Volt/var Control Strategies in LINK-Based Smart Grids with a High Photovoltaic Share. Energies, 14(18), p.5641.

12. Skamyin, A., Belsky, A., Dobush, V. and Gurevich, I., 2022. Computation of Nonlinear Load Harmonic Currents in the Presence of External Distortions. *Computation*, *10*(3), p.41.

13. Shaaban, S.M. and Mesalam, Y.I., 2022. SVC Parameters Optimization Using a Novel Integrated MCDM Approach. *Symmetry*, *14*(4), p.702.

14. Martins Bezerra, P.A., Krismer, F., Kolar, J.W., Khaddam-Aljameh, R., Paredes, S., Heller, R., Brunschwiler, T., Francese, P.A., Morf, T., Kossel, M.A. and Braendli, M., 2021. Experimental Efficiency Evaluation of Stacked Transistor Half-Bridge Topologies in 14 nm CMOS Technology. Electronics, 10(10), p.1150.

15. Khalid, R., Javaid, N., Al-Zahrani, F.A., Aurangzeb, K., Qazi, E.U.H. and Ashfaq, T., 2019. Electricity load and price forecasting using Jaya-Long Short Term Memory (JLSTM) in smart grids. Entropy, 22(1), p.10.

16. Khalid, R., Javaid, N., Al-Zahrani, F.A., Aurangzeb, K., Qazi, E.U.H. and Ashfaq, T., 2019. Electricity load and price forecasting using Jaya-Long Short Term Memory (JLSTM) in smart grids. Entropy, 22(1), p.10.

17. Albogamy, F.R., Khan, S.A., Hafeez, G., Murawwat, S., Khan, S., Haider, S.I., Basit, A. and Thoben, K.D., 2022. Real-Time Energy Management and Load Scheduling with Renewable Energy Integration in Smart Grid. Sustainability, 14(3), p.1792.

18. Kulmala, A., Repo, S. and Järventausta, P., 2014. Coordinated voltage control in distribution networks including several distributed energy resources. *IEEE Transactions on Smart Grid*, *5*(4), pp.2010-2020.

19. Hird, C.M., Leite, H., Jenkins, N. and Li, H., 2004. Network voltage controller for distributed generation. *IEE Proceedings-Generation, Transmission and Distribution*, *151*(2), pp.150-156.

20. Pfajfar, T., Papic, I., Bletterie, B. and Brunner, H., 2007, October. Improving power quality with coordinated voltage control in networks with dispersed generation. In *2007 9th International Conference on Electrical Power Quality and Utilisation* (pp. 1-6). IEEE.

21. Bevrani, H. and Shokoohi, S., 2013. An intelligent droop control for simultaneous voltage and frequency regulation in islanded microgrids. *IEEE transactions on smart grid*, *4*(3), pp.1505-1513.

22. Engler, A. and Soultanis, N., 2005, November. Droop control in LV-grids. In *2005 International Conference on Future Power Systems* (pp. 6-pp). IEEE.

23. El Moursi, M.S., Zeineldin, H.H., Kirtley, J.L. and Alobeidli, K., 2014. A dynamic master/slave reactive power-management scheme for smart grids with distributed generation. *IEEE Transactions on Power Delivery*, *29*(3), pp.1157-1167.

24. Kim, Y.J., Kirtley, J.L. and Norford, L.K., 2015. Reactive power ancillary service of synchronous DGs in coordination with voltage control devices. *IEEE Transactions on Smart Grid*, *8*(2), pp.515-527.

25. Moutis, P., Georgilakis, P.S. and Hatziargyriou, N.D., 2016. Voltage regulation support along a distribution line by a virtual power plant based on a center of mass load modeling. *IEEE Transactions on Smart Grid*, *9*(4), pp.3029-3038.

 doi:10.20944/preprints202204.0275.v1

26. Souza, P., Filho, J.C., Ferreira, D.F., Filho, J.M., Filho, H.K.R. and Pereira, N.B., 2020. Cluster-Based Method to Determine Base Values for Short-Term Voltage Variation Indices. *Energies*, *14*(1), p.149.

27. Corigliano, S., Rosato, F., Ortiz Dominguez, C. and Merlo, M., 2021. Clustering techniques for secondary substations siting. *Energies*, *14*(4), p.1028.

28. Valenzuela, A., Inga, E. and Simani, S., 2019. Planning of a resilient underground distribution network using georeferenced data. *Energies*, *12*(4), p.644.

29. Haider, W., Hassan, S.J.U., Mehdi, A., Hussain, A., Adjayeng, G.O.M. and Kim, C.H., 2021. Voltage profile enhancement and loss minimization using optimal placement and sizing of distributed generation in reconfigured network. *Machines*, *9*(1), p.20.

30. Karimi, M., Farshad, M., Hong, Q., Laaksonen, H. and Kauhaniemi, K., 2020. An islanding detection technique for inverter-based distributed generation in microgrids. Energies, 14(1), p.130.

31. Mahesh, K., Nallagownden, P. and Elamvazuthi, I., 2016. Advanced Pareto fronts non-dominated sorting multi-objective particle swarm optimization for optimal placement and sizing of distributed generation. *Energies*, *9*(12), p.982.

32. Karunarathne, E., Pasupuleti, J., Ekanayake, J. and Almeida, D., 2021. The optimal placement and sizing of distributed generation in an active distribution network with several soft open points. *Energies*, *14*(4), p.1084.

33. Liu, W., Luo, F., Liu, Y. and Ding, W., 2019. Optimal siting and sizing of distributed generation based on improved nondominated sorting genetic algorithm II. *Processes*, *7*(12), p.955.