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Reduction of Losses and Improvement of Voltage Profile in Radial Distribution Network by Interconnection of Feeders

Mecon Joshi[1*], Manoj Godar[2]
[1] *Dept. of Electrical Engineering, Pulchowk Campus, IOE, TU, Nepal, E-mail: meconjoshi@gmail.com*
[2] *Dept. of Electrical Engineering, Pulchowk Campus, IOE, TU, Nepal, E-mail: manojgodar46@gmail.com*

Abstract— High penetration of photovoltaic systems is creating various issues in the distribution network such as increased power losses and violation of voltage limits. The voltage violation occurs at the point of common coupling in the network especially at midday when the photovoltaic generation is high and the loading of the network is low. The approach considered in this paper to mitigate these issues is by the interconnection of radial feeders. The interconnection of feeders allows the direct connection of areas having high photovoltaic power output to areas with high loading at midday. When the position is properly chosen, the interconnection reduces the network losses and also mitigates the voltage violation at the susceptible areas. In this paper, the CIGRE low-voltage European distribution network has been considered and its three subnetworks have been interconnected in various configurations. The interconnection minimized the daily network losses by 17.28% at the optimum case and was also successful in mitigating overvoltage in the network. The working mechanism of this approach is straightforward while giving the desired results.

Keywords— Distribution Networks, Radial Lines, PV Penetration, Loss Reduction, Voltage Profile

Introduction

Rooftop PV (photovoltaic) installation has gained popularity worldwide in recent years due to its renewable nature, easy installation and economic advantages from net metering. These are typically grid-connected PV systems that supply the loads connected to the building and supply excess energy into the grid. Distribution networks have been designed in the past without the consideration of connecting such energy producing systems and the bidirectional flow of power arising from them. So, the installation of grid-connected PV systems at a high penetration level creates various problems in the distribution network such as voltage rise, voltage unbalance, harmonics, power loss and power quality [1].

Rooftop PV systems are installed in common households at 400V distribution voltage level. At this voltage level there is typically no voltage regulation equipment. This causes many voltage violations to occur in low voltage (LV) networks which is one of the major problems at high PV penetration levels [2]. PV penetration level is a mathematical term that gives the fraction of energy that has been supplied by the PV system to the load on an annual basis. It is expressed as:

$$PV_{pen} = \frac{Total\ Energy\ Generated\ by\ PV\ System\ in\ a\ Year}{Total\ Energy\ Consumed\ by\ the\ Load\ in\ a\ Year} \quad (1)$$

The voltage violations occur at midday when the generation from PV systems is highest and the load is typically low. Distribution networks have high R/X ratio, so this excess active power also impacts the voltage at the nodes of the network where PV systems are connected [3]. This is clear from the mathematical expression for voltage drop in a line given as:

$$V_{drop}(pu) = R(pu) * P(pu) + X(pu) * Q(pu) \quad (2)$$

Another issue that arises at high PV penetration level is the increased power losses in the system. At low PV penetration level, the system loss gets reduced due to the localized supply of power. However, at high PV penetration, the flow of excess active power generated from the PV system causes the losses to increase [2]. A number of different methods such as active power curtailment of PV systems, reactive power control, control using on-load tap changers (OLTC) and energy storage have been considered for mitigating the overvoltage issues [4].

Paper [5] proposes a method to reduce system losses and mitigate overvoltage in the distribution network by the interconnection of radial feeders. This approach is based on the principle of using lines to connect two feeders so that excess PV generation from one feeder can be consumed by the load in the other feeder. In [5], it

** Corresponding Author*

has been considered for a 6.6kV distribution network with a central focus on evaluating the reliability of such configuration. In this paper, the interconnection of radial feeders of a 400V distribution network with no OLTC is attempted, and its effectiveness in reducing power loss and mitigating overvoltage has been studied. The study has been carried out on the CIGRE European LV Distribution Network with its three subnetworks.

Literature Review

The interconnection of a heavily loaded feeder with a lightly loaded feeder can help balance unevenly distributed loads, thereby improving the voltage profile and significant power loss reduction can be made between two buses with considerable voltage differences in a radial distribution system [6].

According to [7], network reconfiguration has been extensively studied in the past for objectives such as loss minimization and load balancing using various kinds of heuristic and evolutionary algorithms. Due to the increasing adoption of distributed generation (DGs) such as rooftop PV systems, algorithms are being developed to also consider the bidirectional power flows arising from them. The authors of [7] have developed an algorithm for loss minimization which is efficient and also suited for real time applications. The effectiveness and feasibility of hourly network reconfiguration have been studied in [8].

Several studies have developed methods to improve the efficiency and voltage profile of radial distribution networks, specifically in the context of increasing PV penetration. One notable approach explained in the paper

[5] examines the impact of distributed generations (DGs) on radial feeders and evaluates their effects when feeders are reconfigured into a loop system through tie-switches. The radial feeders with interconnections between them have been termed as radial-loop configuration. According to the authors, this configuration reduces the active power losses while maintaining voltage regulation, even under varying PV penetration levels. However, reliability of supply to the customers needs to be considered at fault conditions before the implementation of such configuration.

Methodology

Network under consideration

The CIGRE European LV Distribution Network has been considered in this paper for the study of optimal interconnection of lines. The network consists of 3 subnetworks namely Residential, Commercial and Industrial subnetworks. Each subnetwork is a radial feeder connected to the 20kV bus through an appropriately sized transformer stepping down the voltage to 400V. The 3 feeders have balanced three-phase loads of different capacities interconnected by underground or overhead lines of varying sizes. Also, the 3 subnetworks have different load curves which are shown in Figure 1.

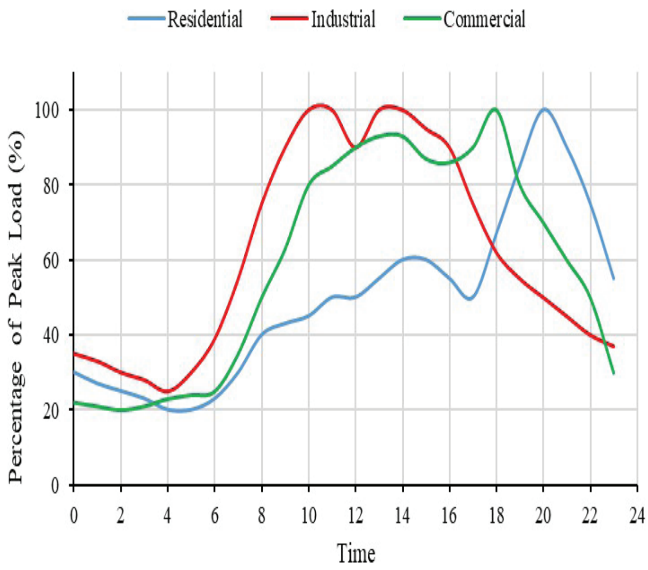

Fig 1. Load Curve of Residential, Industrial and Commercial Subnetwork

Additionally, grid-connected PV systems have been added to this network, which can be considered as rooftop PV installations. The capacity of PV systems installed at a node is taken to be 1.5 times the load connected to the same node. Further, a 150kW PV system has been connected at the end of the Industrial subnetwork and a 120kW PV system has been connected at the end of the Residential subnetwork to consider a more challenging condition. All the PV inverters have been configured to work in unity power factor. The simplified diagram of the entire network is shown in Figure 2. The diagram only includes the names of important nodes and excludes neutral earthing points and poles which are not connected to any load. It should be understood that each of the nodes represented by a white square also has a grid-connected PV system connected to it. The capacity and power factor of each load and PV system have been compiled in Table I.

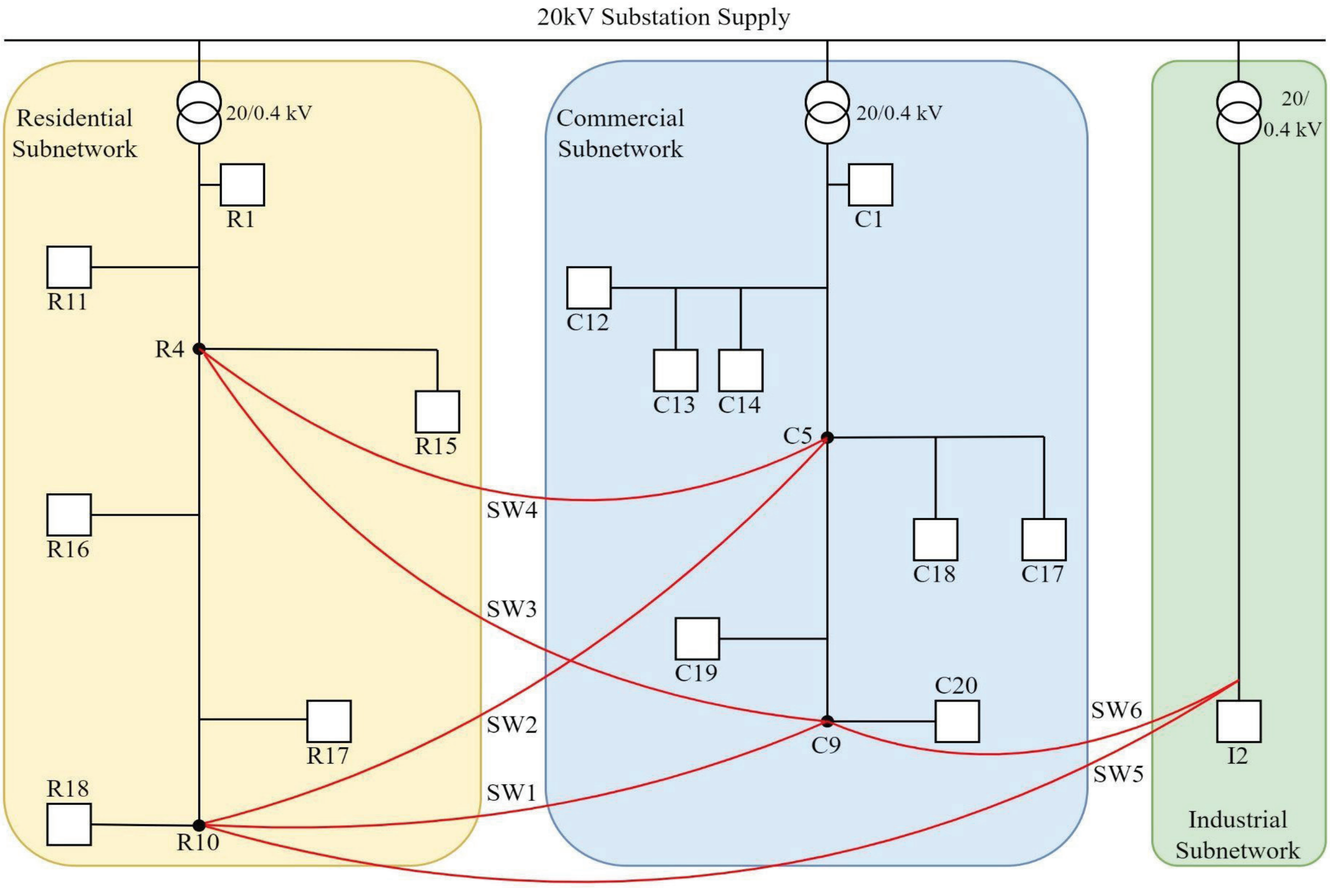

Fig 2. Simplified Diagram of the CIGRE LV European Distribution Network with interconnecting switches

Table i

Values of load and pv systems connected at various nodes of the network

Name of Node	Load (kVA)	pf	PV Size (kW)	Name of Node	Load (kVA)	pf	PV Size (kW)
R1	200	0.95	300	C1	120	0.9	180
R11	15	0.95	22.5	C12	20	0.9	30
R15	52	0.95	78	C13	20	0.9	30
R16	55	0.95	82.5	C14	25	0.9	37.5
R17	35	0.95	52.5	C17	25	0.9	37.5
R18	47	0.95	190.5	C18	8	0.9	12
I2	100	0.85	300	C19	16	0.9	24
				C20	8	0.9	12

Interconnection of Feeders

The feeders are interconnected by imaginary switches 1 to 6 as shown in figure 2. Turning the imaginary switch on represents the existence of a line connecting two parts of the network and turning it off represents the removal of such a line. The switches used for the interconnection of lines are considered to connect two parts of the network with 70mm^2 aluminum conductors, which have also been used in other parts of the distribution network. The different switches are assumed to have different line lengths as given in Table II, fixed according to the geometry of the network.

Table ii

Length of lines used for connection by different switches

Switch	Nodes Connected	Length	Switch	Nodes Connected	Length	Switch	Nodes Connected	Length
SW 1	R10-C9	100m	SW 3	R4-C9	150m	SW 5	R10-I2	100m
SW 2	R10-C5	150m	SW 4	R4-C5	100m	SW 6	I2-C9	100m

Working Principle

Interconnection of feeders in a radial line leads to the improvement of voltage profile and reduction in losses. The interconnection of lines allows power to flow from an area with high PV output to an area having large loads. Thus, the interconnection provides an alternative path to maintain the balance of power generation and consumption within local regions of the network.

Results

The model of the network described in the previous section was created in OpenDSS and simulations were carried out for various cases by connecting different switches and their combinations.

Daily System Energy Losses

The total daily system loss for the case without any switches connected and with a single switch has been shown in Table

Table iii

Daily energy loss in the entire network with interconnection through one switch

Default Network: 272kWh	SW 1: 255kWh	SW 3: 264kWh	SW 5: 259kWh
	SW 2: 255kWh	SW 4: 263kWh	SW 6: 232kWh

As seen from Table III, the network without any modifications has 272kWh losses per day. This loss has been reduced to a minimum value of 232kWh when the lines are interconnected through switch SW6, which is a reduction of 14.71% in daily energy loss value.

Next, a combination of two switches has been considered to observe the losses. The first switch connects the Residential and Commercial Lines (SW1 to 4) while the second connects the Industrial Line to either the Residential or Commercial Line (SW5 and 6). The eight different valid connections and their corresponding losses have been shown in Table IV.

Table iv

Daily energy loss in the entire network with interconnection through the combination of two switches

Switch No.	Loss (kWh)	Switch No.	Loss (kWh)		Switch No.	Loss (kWh)	Switch No.	Loss (kWh)
SW 1&5	236	SW 3&5	250		SW 1&6	229	SW 3&6	229
SW 2&5	235	SW 4&5	249		SW 2&6	225	SW 4&6	230

The minimum loss obtained in the network is 225kWh when switches SW2 and SW6 are closed. The interconnection has reduced the energy loss in the network by 17.28%. This is lower than the minimum loss obtained by the use of only one switch but only by 7kWh. Although the difference in the value of loss is very small, the connection of 2 switches has another advantage which is to improve the voltage profile of the entire network.

Voltage Profile at noon without Interconnection

The voltage profile of the three subnetworks at midday has been plotted in Figure 3. The distribution network has a high R/X ratio due to which the excess active power generated by PV systems has an impact on voltage magnitude at nodes. Because of that, the Residential and Industrial subnetworks have voltages rising at the nodes away from the source, and the voltage value is highest at the end of the feeder. The Residential subnetwork in particular is more susceptible to high node voltages even though it has a smaller PV system installed at its end, because of its light loading at noon. The rise in voltage is not seen in the Commercial subnetwork because it doesn't have a large PV system at the end of the feeder.

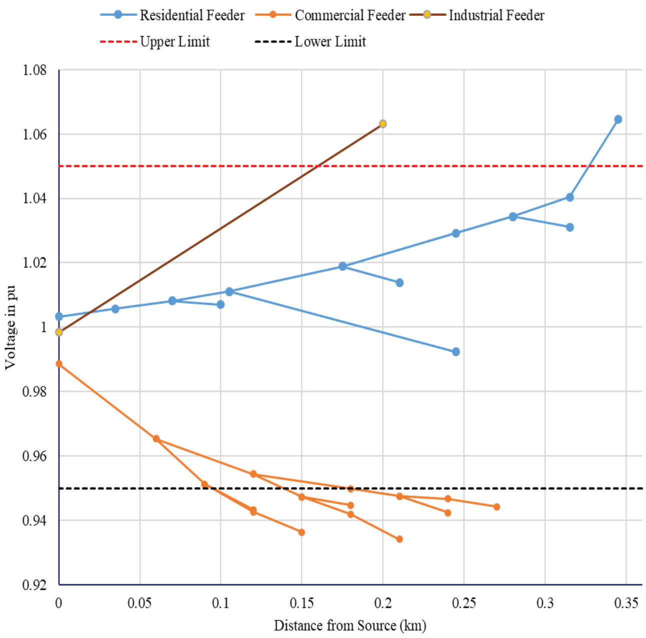

Fig 3. Variation of node voltage with distance in Residential, Commercial and Industrial feeder at noon

24-hour Voltage Variation

The variation of node voltage throughout the day at different nodes of the network has been shown for the case of no interconnection of lines in Figure 4 and with interconnected lines in Figure 5. The node voltages at only five important nodes with three nodes at the end of the feeder and two at the middle of Residential and Commercial feeders have been shown.

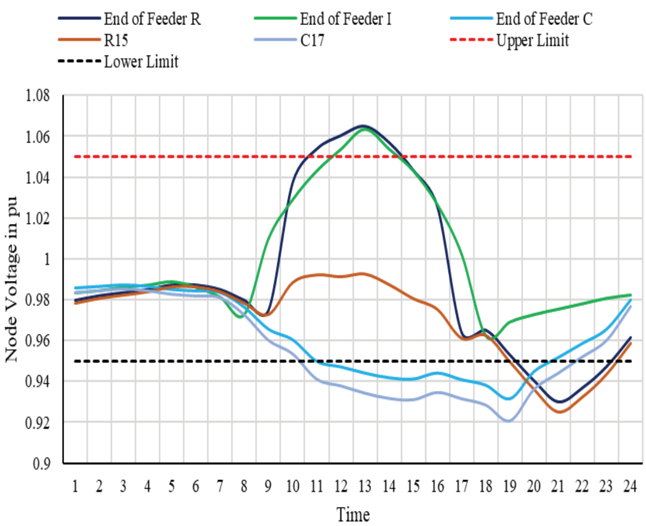

Fig 4. Voltage values at various nodes of the network throughout the day without interconnection of feeders

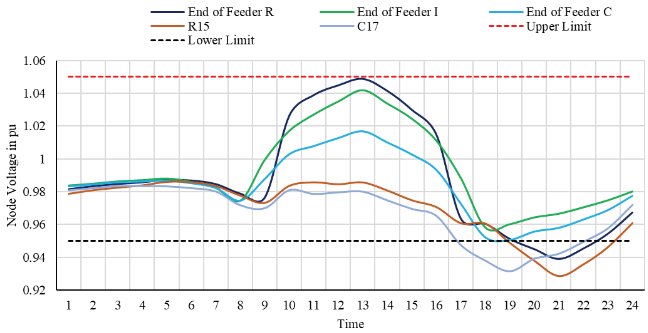

Fig 5. Voltage values at various nodes of the network throughout the day with feeders interconnected by SW2 and SW6

It can be seen from Figure 4 that the node voltage exceeds the upper limit at the end of Residential and Commercial feeders during peak irradiance hours of midday. The end of the Residential feeder is in overvoltage condition for longer hours than the Industrial feeder because of the nature of its load curve. As explained in previous sections, this overvoltage is due to the high PV generation and low loading of the feeder.

Now, when the feeders are interconnected, the end of the Residential feeder and Industrial feeder are connected respectively to the middle and end of the Commercial feeder. The commercial feeder has comparatively less PV generation and high loading at midday. So, the excess power in the Residential and Industrial feeder gets diverted to the loads in the Commercial feeder. This helps to maintain the balance between active power generation and consumption and reduces the exceeded node voltages. The reduction in node voltages at the end of Residential and Industrial feeders can be clearly seen in Figure 5, through comparison with Figure 4.

Power flow through the Interconnecting Lines

The power flowing through the two lines interconnecting the feeders throughout the day has been plotted in Figure 6. It can be seen that the power flow is very small from midnight to morning, maximum during day time and low during evening. At midday, the excess PV generation from Residential and Industrial feeders flows through the interconnecting lines to loads in the Commercial feeder. This is responsible for the high-power flow in the daytime. It can also be noted that the power flow is negative through SW2 from evening to night. This means that the power is flowing from the lightly loaded Commercial feeder into the Residential feeder which has high loading in the evening. It can be verified that the power flow from these lines has contributed to the reduction in network losses and mitigation of overvoltage in the end nodes.

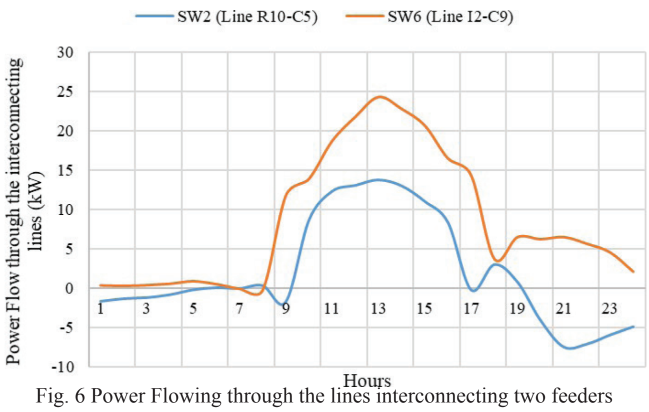

Fig. 6 Power Flowing through the lines interconnecting two feeders

(SW2 and SW6)

Conclusion

Thus, by the strategic interconnection of radial feeders by considering the location of grid-connected PV systems and load curves of the feeders, the entire network can be optimized to have lower losses and better voltage regulation. The principle based on adding lines to maintain the balance of power generated and power consumed at different parts of the network has been found to be effective in a 400V distribution network. The interconnection of feeders by lines was able to reduce the network losses by a maximum value of 17.28% while keeping all the nodes at every feeder below the upper voltage limit. Because of the simplicity of this approach, it can be readily implemented in appropriate networks in the real world.

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