Generating Original Daily Load Curves of Feeders with Distributed Photovoltaic Plants

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Abstract**—Distributed Solar Photovoltaic (DPV) plants connected along distribution feeders change the original daily load curves of these feeders into daily net-load curves that return lower peak load values. Doing medium voltage (MV) network design and development based on net-peaks may affect the reliability of distribution feeders with DPV connections. On the other hand, estimating original peaks by arithmetical summation of net-peak and total DPV ratings returns over-estimated peaks. This reduces the efficiency of network assets utilization and, consequently, overestimates network expansion requirements. A distribution planning tool (DPT) has been developed to generate the original daily load curves of distribution feeders without DPV impact, from which original peaks can be obtained and used in planning procedures. The DPT is developed to operate with actual weather data and DPV design specifications. It has been applied on existing case study of 11kV feeder considering different scenarios.**

Index Terms**—distributed solar photovoltaic, daily load curves, distribution planning**

I. Introduction

Integration of Distributed Solar Photovoltaic (DPV) plants changed the trend of hierarchical power flow from substations to consumers [1]. Furthermore, most of medium voltage (MV) distribution feeders have been designed to operate radially that may impose further challenges on the planning of distribution networks with high PV penetration [2]. Of these challenges is the uncertain variability of DPV power generation along MV distribution feeders. Such impact changes the shape of daily load curves of feeders into daily net-load curves, or what's called nowadays 'duck curve', that to be considered by planning engineers [3], [4]. Thus, peak loads required for MV network design and development procedures will be determined based on net-load curves that return lower peaks than original ones without DPV impact [5]. Applying such procedures with net-peaks may affect the reliability of distribution feeders in the events of passing clouds, sand storms, and malfunctions of DPV plants; where net-load curves are returned -totally or partially- to their original shapes. To avoid this concern, distribution network design and development procedures are deemed to be conducted based on original peak load values without DPV impact.

For planning purposes, the traditional trend to estimate the original peak of certain distribution feeder is by taking the arithmetical summation of measured net-peak of that feeder and total rating of operated distributed generation plants connected to it. However, for feeder with DPV plants, this practice returns overestimated original peak due to the time mismatch of feeder net-peak and peak generation of DPV plants. Because of that many utilities estimate the contribution of DPV plants to peak demand in the range of 30%-50% of their rating [6]; while others estimated it by even 10% of rating [7].

Note that, from distribution planning standpoint, peak loads are used to forecast the load growth and plan for capacity expansion of the network [8]. This means that overestimated peaks result in overestimation of network expansion requirements and reduction in assets utilization efficiency.

In this work, a distribution planning tool (DPT) has been developed for the planning procedures of Dubai Electricity & Water Authority (DEWA). It generates the shapes of original daily load curves, without DPV impact, based on net-load curve values. Original peaks can then be obtained from the original curves and used in existing procedures. The main part of the DPT is a physical PV power model to simulate the production of DPV plants. It has been arranged to provide the model with the specifications of connected DPV plants. Additionally, the model is provided with actual Global Horizontal Irradiance (GHI) and ambient temperature (*T*) data. The daily DPV power profiles are then simulated and added to their corresponding net-load curves to generate original daily load curves. The impact of net-peak on the reliability or efficiency of assets utilization is explained in Section II. Section III is dedicated to the development of DPT; while Section IV explains the utilization of DPT on actual case study, and Section V is left for conclusion.

II. MV Netwwok Design with DPV

Integration of DPV plants in distribution network pulls down its daily load curves during sunshine hours creating

Manuscript received March 5, 2018; revised September 13, 2018; accepted September 13, 2018.
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doi: 10.18178/ijeetc.8.2.89-94

net-load curves, or what's called 'duck curves' [3]. Thus, SCADA meter at feeder's head will measures net-peak, which is lower than original peak [5]; see Fig. 1. Note that, for reliability issues, net-peak is unacceptable. On the other hand, estimating the original peak by arithmetical summation returns overestimated peak that reduces assets utilization efficiency and, consequently, overestimates network expansion requirements.

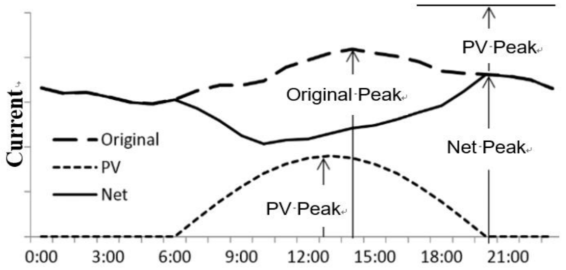

Fig. 1. Impact of DPV generation on feeder daily load curve.

Fig. 2 shows an actual example that compares 3 successive daily load curves of an existing 11kV feeder (Feeder.1) in Jul 2016 and Jul 2017, before and after the interfacing of a DPV plant of 1 MWp. The figure shows obvious reduction in the later load curves during sunshine hours due to the DPV plant impact.

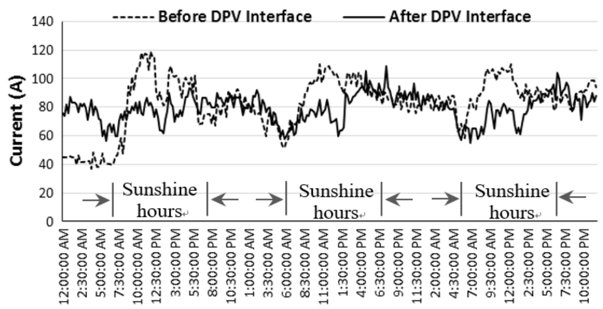

Fig. 2 Measured curves of Feeder.1before & after DPV.

III. Peak-Load Correction of Feeders with DPV

A distribution planning tool (DPT) has been developed to generate original daily load curves of distribution feeders without DPV impact. The main part of the tool is a physical PV power model, for original peak load calculation, that consists of the following modules.

A. Physical PV Power Model

PV power models can be developed on statistical or physical basis [9]. Statistical model needs training datasets of historical PV power data, which is still not much with DEWA due to the recent launch of Shams Dubai program of solar PV rooftop in Dubai. Because of that, the DPT has been developed with a physical PV power model that operates with actual weather data and design specifications of connected DPV plants. In this context, the PV power (PVP) can be calculated as follows [5]:

$$\mathrm{PVP} = \frac{G}{G_{\mathrm{STC}}} \times \mathrm{PVP}_{\mathrm{STC}} \times \left[1 + \frac{\mathrm{PTC}}{100} \times \left(T - T_{\mathrm{STC}}\right)\right] \tag{1}$$

where

PVP - PV power at actual conditions, Wp.
G - Actual global irradiance on PV panels, W/m^2.
T - Actual PV cell temperature, °C.
STC- Standard conditions (G=1000 W/m^2 & T= 25°C).
PTC - Power temperature coefficient, -%/C.

For accurate results, the PVP is corrected to consider irradiance-dependent efficiency of PV panels. Hence, corrected PV power (PVPc) is expressed as follows [10]:

$$\mathrm{PVP}_{\mathrm{C}} = \mathrm{PVP} - K \times \mathrm{PVP}_{\mathrm{STC}} \times F \tag{2}$$

According to [4], K factor can be expressed as follows:

$$K = \frac{200}{G_{\mathrm{STC}}} \times \Delta\mathrm{Eff}_{200} \tag{3}$$

where $\Delta\mathrm{Eff}_{200}$ is the relative reduction in PV panels efficiency at G=200W/m^2 comparing to G_{STC}. The values of $\Delta\mathrm{Eff}_{200}$ are given as 0.085, 0.125, & 0.095 for mono-Si, poly-Si and thin-film respectively [11], [12].

Application of (3) with the above values of $\Delta\mathrm{Eff}_{200}$ gives K equals to 0.017 for Mono-Si, 0.025 for Poly-Si, and 0.019 for Thin-film.

As for F, the two formulas are applied [10]:

$$F = \frac{G_{STC} - G}{G_{STC} - 200}; \text{ for } G > 200\mathrm{W/m}^2 \tag{4a}$$

$$F = 1 - \left(1 - \frac{G}{200}\right)^4; \text{ for } G \le 200\ \mathrm{W/m}^2 \tag{4b}$$

B. Tilt Factor

The outcomes of PV power model are considerably influenced by the variation of PV panels inclinations. Hence, derivations of tilt factor (Tf) have been developed in this concern.

Note that basic weather stations normally measure Global Horizontal Irradiance (GHI). On the other hand, rooftop PV panels are likely to be tilted according to buildings structure. Hence, tilted G is expressed in terms of beam, diffused and reflected components as follows [13]:

$$G_T = B_T + D_T + R_T \tag{5}$$

where G_T stands for the G normal to tilted surface; B_T, D_T and R_T is the beam, diffused and reflected G_T component.

Long derivations have been developed to solve (5) that ended up with generating Tf values based on the following formula:

$$\mathrm{Tf} = r_b B_h + r_d D_h + 0.5\rho\left(1 - \cos\beta\right) \tag{6}$$

Note that variables of (6) can be derived based on [13-17] where r_b and r_d are ratios of beam and diffused irradiances normal to tilted surface, and those normal to ground. While B_h & D_h are beam and diffused factors in terms of daily clearance index, ρ is the ground reflectivity and β is the tilt angle.

To this end, PVP_c values of (2) in each time step is multiplied by its associated Tf value to calculate PVP_c at any tilt angle. Consequently, the ac power of DPV plant is:

$$PVP_{ac(i)} = PVP_{C(i)} \times Tf_{(i)} \times PR \quad (7)$$

where PVP_{ac} stands for the AC power generated by the DPV plant, PR is the performance ratio of DPV (~ 0.75 - 0.9), and *I* is the time steps index.

The PV Power model has been applied on existing 13 MWp PV power plant in Dubai, using actual GHI and T data. For validation, the daily PV power profiles generated by the model have been compared with the counterpart power profiles measured by the plant. Fig. 3 illustrates this comparison for different days from different months in 2015, which approve high level of congruence.

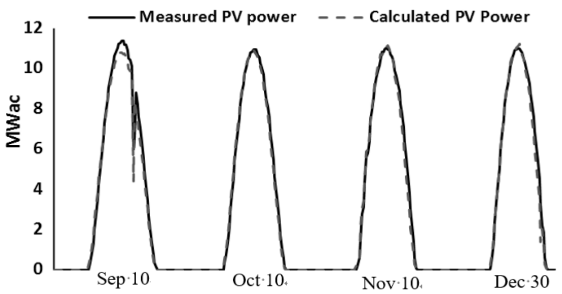

Fig. 3. Validation of the developed PV power model.

C. Calculator of Original Peak Load

Original daily load curves of feeders are generated in amperes by adding measured net-peak current in each time step with its corresponding current from connected DPV plants. Emphases is placed to consider that DPV current are totally active component as PV inverters are usually set to operate at unity power factor. Hence, original current at time step *i* is calculated as follows:

$$Iorg_{(i)} = \sqrt{\left(Inet_{P(i)} + \frac{PVP_{ac(i)}}{\sqrt{3}V}\right)^2 + \left(Inet_{Q(i)}\right)^2} \quad (8)$$

where Iorg is the calculated original current, Inet is the measured net-load current, P and Q stand for the active and reactive components, and *i* is the time step index.

As an example, (8) has been applied on existing 11 kV feeder (Feeder.2) with 600 kWp DPV plant. The measured Inet curve, calculated Iorg curve (by the DPT), and the over-estimated Iorg curve (by arithmetical summation) are shown in Fig. 4. The figure shows that measured Inet-peak was 27.1 A, while calculated Iorg-peak is 38.51 A. Additionally, Fig. 4 shows that traditional estimation practice by arithmetical summation results in over-estimated Iorg-peak of 55.8 A.

For validation issues, the figure contained a previous actual Iorg curve, 2 weeks before the connection of DPV plant. As it can be seen, it shows similar trend to calculated Iorg load curve.

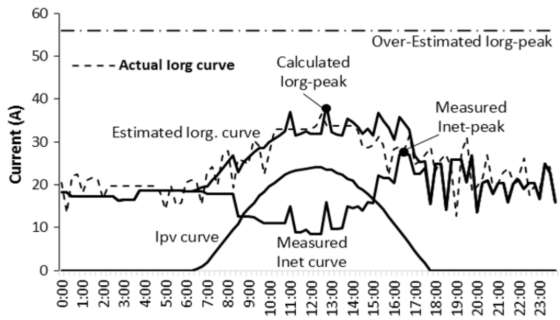

Fig. 4. Application of (7) on Feeder.2 on Nov. 5, 2015.

D. Finder of DPV Malfunctions Days

Applying (7) in each time step -based on measured Inet values along with actual GHI and T data- generates original daily load curves from which original peak can be obtained. However, during times of DPV plants malfunctions or isolation, the net-load curve goes up to its original shape and, consequently, Inet becomes Iorg. In such a case, applying (7) will generate original daily load curves of highly overestimated values that in turn result in highly overestimated peak.

To avoid such inconvenience, this work derived and validated the below method to find and exclude DPV malfunction and isolation days, if any, from the calculation of original peaks.

Let $Iorg_{d\_avg(j)}$ is the average of original daily load curve generated in day *j*. Hence, monthly average of the same is:

$$Iorg_{m\_avg} = \frac{1}{m}\sum_{j=1}^{m} Iorg_{d\_avg(j)} \quad (9)$$

Let $Iorg_{d\_peak(j)}$ is the peak of original daily load curve generated in day *j*. Hence, the following condition is applied:

$$\text{If } \frac{Iorg_{d\_avg(j)}}{Iorg_{m\_avg}} > \text{Threshold} \rightarrow \text{exclude } Iorg_{d\_peak(j)} \quad (10)$$

where

$Iorg_{m\text{-}avg}$ - Monthly average of daily Iorg curves.
Threshold - Selected value between 1.1 – 1.3.
m - Number of days in the month.

Thus, resultant original peak generated for the feeders is:

$$Iorg_{m\_peak} = \text{Max}\left[Iorg_{d\_peak(j)}\right]_{j=1\rightarrow m} \quad (11)$$

For verification, the method was applied on the original peak load calculation of Feeder.2 from Oct 26, 2015 to Dec 31, 2016. The method identified the days of Nov 3, 2015 and Mar 16-19, 2016 and excluded them from the process.

Fig. 5 presents snapshots from the monitoring system for one of the two 300 kW inverters of the DPV plant connected to Feeder.2. It shows no/limited PV production during these days due to DPV plant malfunction or isolation.

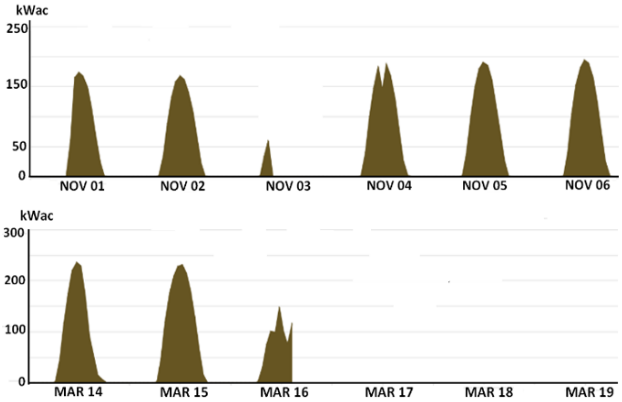

Fig. 5. Production of DPV plant showing 2 days of DPV off.

A. *Estimator of Power Factor Variations*

Power utilities manage their network to keep high power factor (PF) values and, therefore, most of electrical loads are likely manufactured to operate at high PF values. To this end, DEWA persists to keep the PF values of its MV feeders at around 0.9. It connects Automatic Capacitor Banks (ACB) to many of its distribution transformers (DT) to correct PF values to around 0.9, even with the change of loads nature. However, this value will be no longer controlled when DPV plants are integrated and no capacitor banks are connected. The point is that PV inverters are most likely set to operate at unity PF the matter that results in ever changing active power production by these inverters into feeders. To this end, we may assume the two conditions of; feeders that majority of their DTs are with capacitor banks and vice versa. No issues with the earlier condition as capacitor banks can reasonably keep PF value close to 0.9, which is not the case with the former condition of no capacitor banks.

B. *PF Variation Estimation with no Capacitor Banks*

Many power utilities have only current meters at the heads of MV distribution feeders. Hence, variations of PF due to the impact of DPV plants are not measured, which directly affects Inet values of (8). To solve this issue, a method has been derived in this work to estimate phase shift variations, assuming original PF without DPV impact is always close to 0.9. The method, illustrated in Fig. 6, consists of:

Step 1: Generate initial value for Iorg (Iorg.ini) by adding DPV current (I_{PV}) to the measured value of Inet (Inet.act).

Step 2: Assume PF of 'Iorg.ini' is 0.9, then apply the formula of step 2 to approximate a phase shift angle for 'Inet.act' by using Ipv in per-unit of the active component of 'Iorg.ini' (Iorg.ini.p). Note that the formula has been generated experimentally by assuming 10 Ipv steps, in per-unit of known Iorg (0.1 to 1.0), then to calculate the resultant shift angle in each step. The results are then plotted to generate the said formula.

Step 3: Use 'Inet.act' and its approximated shift angle, along with the known Ipv to estimate Iorg value (Iorg.esti). Note that further correction factor has been determined, by experiment, to get more accurate 'Iorg.esti' for 'Ipv.pu' > 0.6 of 'Iorg.ini.p'.

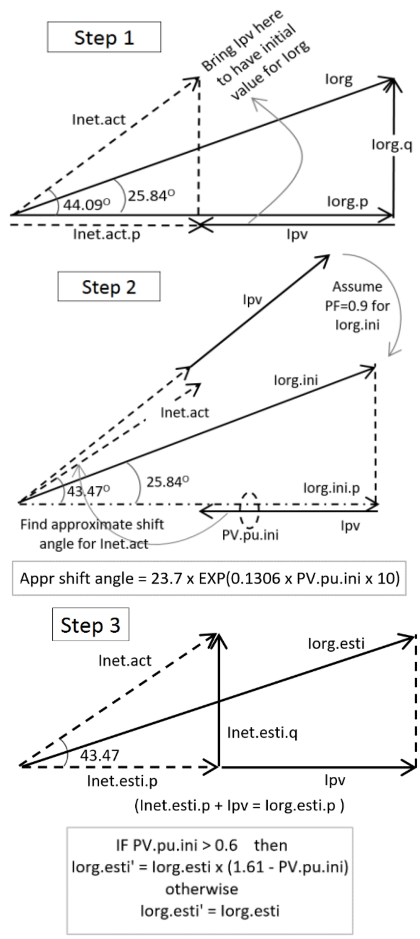

Fig. 6. Estimation of Iorg with variations of PF values due to DPV, and with absence of automatic capacitor banks.

The method of PF variations estimation has been verified in two stages. In stage 1, different values of Iorg are set, all at PF=0.9. For each value of these, 10 steps of 'Ipv.pu' (0.1→1.0) are assumed to be injected, and resultant 'Inet' is calculated directly by trigonometry.

In stage 2, the calculation process is reversed where the same 'Inet' values calculated in stage 1 are set, and Iorg values are estimated by applying the three steps of Fig. 6. The verification is considered successful if Iorg values estimated in stage 2 are found congruent with Iorg values that were set to start stage 1.

The verification is applied by setting different values of Iorg (60A to 125A) to calculate Inet from stage 1. The corresponding values of Iorg are then estimated form stage 2. The set and estimated values of Iorg have approved high level of congruence for all Iorg values, with insignificant errors as shown in Fig. 7.

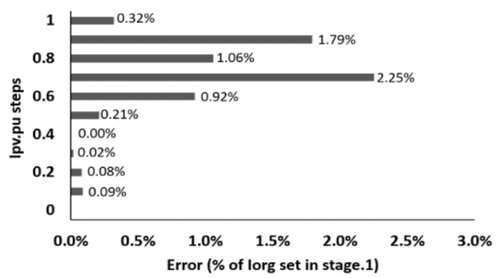

Fig. 7. Percentage errors of Iorg due to estimation of PF values.

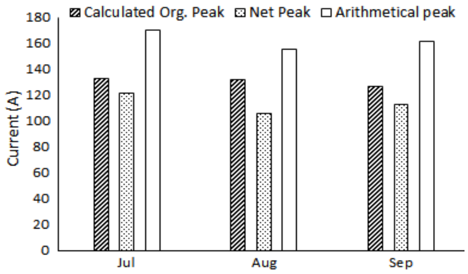

Fig. 8. Calculated-original peak of Feeder.1comparing to measured Net-Peak and Arithmetical peak.

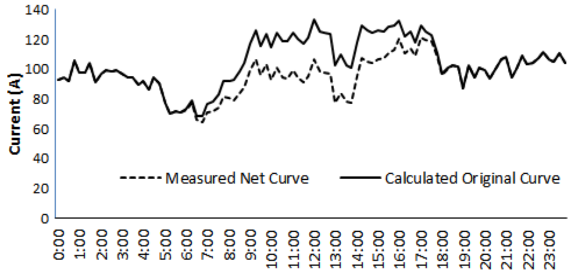

Fig. 9. Measured & calculated-original load curves of Feeder.1 in Jul 18th containing the calculated-original peak of 2017.

IV. Case Study

Highest load demand levels in Dubai are in summer; thus, the developed DPT has been applied on Feeder.1 of Fig. 2 over Jul-Sep 2017. The feeder supplies 10 substations of 11/0.4 kV that two of them are interfaced with DPV plants of total capacity adds up to 1 MWp. Note that DTs along this feeder are likely to have no ACBs, and therefore the PF variation estimation method of Fig. 6 has been integrated with the DPT for this feeder. The ultimate results of DPT application are depicted in Fig. 8, according to which, the measured Net-Peak was 121A, while the peak generated by arithmetical summation was 170A. However, the original peak calculated by applying the DPT was 133 A.

Note that the calculated original peak was found to occur at 12:00 noon of Jul 18, 2017. Fig. 9 shows the net and original calculated load curves of that day.

For verification, Fig. 10 is plotted to depict the daily load curves of same 3 successive days in Fig. 2. In specific, it shows the original load curve in July 2016, before the DPV interface, and calculated original load curve in July 2017 after the DPV interface. The figure shows consistent trends of the two curves, considering the fact of they are in two different years.

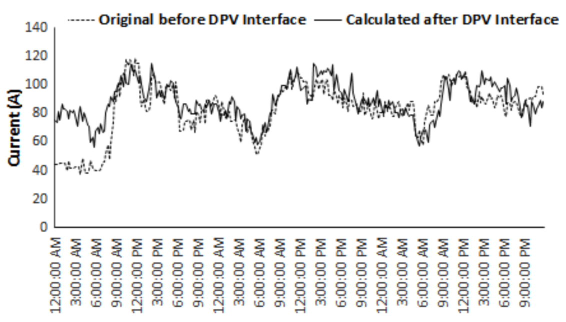

Fig. 10. Measured and calculated original curves of Feeder.1 before and after DPV interface.

It is worth mentioning that in case Feeder.1supplies DTs that are likely to have ACB, the DPT is applied with no need to integrate the PF variation estimation method. Hence, just for experiment, the DPT has been applied one more time on Feeder.1 assuming a plenty of ACBs that maintain PF close to 0.9. The application resulted in ultimate peak of 140 A, which higher than 133 A resulted from the first application. Hence, for more conservative applications, engineers might choose to apply the DPT assuming ACB are always available.

V. Discussion and Conclusion

In many regions of the world, like Dubai, customers used to overestimate their maximum demand when applying to power companies for new connection services. This might be due to flexibility of connection fees. Hence, counting on over-estimated maximum demands to determine the peak load of feeder supplying these customers is turned to be infeasible application to distribution network.

Alternatively, planning engineers use the peak load value -measured by SCADA meter- that is most likely lower than the one derived from the total of maximum demands agreed upon with customers. In case the feeder is interfaced with DPV plants, SCADA meter will measure net-peak that may affect the reliability level of feeder if it has been used directly in distribution planning procedures. Calculating original peak of feeder by arithmetical summation of net-peak and rating of DPV plants will end up at potentially over-estimated peak as described earlier in this work. Over-estimated peak leads to inefficient assets utilization, and consequently excessive network expansion costs. Under such situation, this work was done to develop a DPT that generates original daily load curves of distribution feeders containing DPV plants, from which original peaks can be obtained. The DPT is designed to use daily net-load curves measured by SCADA meters at feeders' heads. It is worth mentioning that using the developed DPT to simulate the daily DPV production and the shape of original daily load curves, for distribution planning purposes, can reasonably substitute the absence of complicated smart grid services in many power companies.

Note that in regions of inflexible connection fees, customers used to apply for maximum demands that are limited to their actual consumption. Under such situation, distribution planning engineers may have the option of determining original peak load of feeders, with DPV plants, by directly taking the summation of maximum demands supplied by these feeders.

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