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PV Penetration Limits in Low Voltage Networks and Voltage Variations

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ABSTRACT Photovoltaic embedded generation in low-voltage ac networks is quite popular; however, despite its benefits, there are some problems especially when photovoltaic (PV) penetration exceeds certain thresholds. Among others, voltage violation is of prime importance. Our review of the literature focused on PV penetration limits due to voltage violations in low-voltage (LV) networks. The review revealed that voltage violations can occur at a penetration level as low as 2.5% when a large distributed generator (DG) is installed at a single point. Alternatively, a LV network can host a large number of photovoltaic distributed generators (PVDGs), with a penetration level up to 110% if evenly distributed over shorter lengths. However, an LV network has no rules of thumb for safe penetration limits. Penetration-level calculations have been found that they used numerous approaches, which we have analyzed and discussed to adopt a more rational and unified approach. Our literature review revealed that, in LVs, a very high penetration level can be achieved as compared with medium-voltage (MV) networks. However, MV voltage-level control problems impose a limit for PV hosting in LV networks. There is a need to evolve strategies for robust voltage control at the MV level and to develop certain rules of thumb for PV penetration limits in LV networks independent of the MV level, to increase the PV hosting capacity.

INDEX TERMS LV distribution network, PV penetration limits, PV impacts on LV voltage, voltage violations.

I. INTRODUCTION

Photovoltaic embedded generation in low voltage AC networks is a popular renewable energy source [1], [2] and is expected to become cheaper than traditional energy sources in the near future [3], [4]. Solar availability in most areas worldwide has made this static power generation source widely adoptable. In the case of Low Voltage (LV) connected Photovoltaic (PV) systems, land use becomes irrelevant. In most cases it utilizes rooftops, building facades, windows or parking lots, making it convenient, attractive and more environmentally friendly. The Photovoltaic Distribution Generation (PVDG) share in total PV installed capacity in Germany and Australia, as examples, in the recent past has been estimated as 80% and 99% respectively [5], [6] whereas in Europe it was estimated at 49% [7]. The benefits of PVDGs' to the power distribution network are considerable in terms of the deferring of network upgrades, reducing energy loss and enhanced voltage control and management [8]. Despite benefits there are some problems especially when the PV exceeds certain thresholds in the LV network. The traditional electricity networks have been designed for top down energy flows, so a power flow in the opposite direction will certainly give rise to problems. Many issues face the network utility, but the most important is voltage regulation [1], [9].

A voltage rise generally occurs at peak generation hours with little or no load on LV feeders, for two reasons: power flow reversal and reactive power disturbance in the circuit. There have been a number of studies published regarding PV penetration in distribution networks, with most studies addressing medium sized power plants directly connected to Medium Voltage (MV) networks [10]. The majority of these studies focused on the impact of LV embedded PVs on MV level voltage. However in recent years a reasonable number of studies have been published addressing the LV network voltage itself. Given that the LV network based Micro Grid is becoming a basic unit of the future Smart Grid, in terms of numbers, there is clearly a need for more work and development studies focusing on LV network voltage profiles.

Studies we reviewed were based on actual measurements from pilot projects and test beds in academic institutions and industrial organizations and were based on simulations of real networks or standard networks such as IEEE bus systems. The fact that the results from such studies are very much network dependent makes it difficult to generalize for use in other areas or networks. Many factors played a significant role in these investigations, including the network topology, types of network components, climatic conditions, solar irradiance, load profiles, feeder lengths, type and size of conductors, load concentration along feeders, load types, PV concentration & capacity and regulations in the area.

The subject matter from the available studies was investigated and analyzed in our study with a special focus on PV penetration limits in LV networks and the factors affecting it.

The paper has been divided into sections: Section 2 summarizes the benefits and challenges associated with grid connected PV. In Section 3 the PV impacts on the distribution system are discussed, while Section 4 considers the impacts of PVs on LV networks with a special focus on voltage control. In Section 5 we discuss voltage control in LV networks, factors affecting voltage, variations in penetration limits due to differences in regulations and local rules and practices. Conclusions will be drawn in Section 6.

II. GRID CONNECTED PV PROS AND CONS

Traditionally PVs have been considered suitable for standalone systems in remote locations only. The development of smart modern power conditioning units designed specifically to meet grid connection requirements has made the use of PVs equally attractive in urban centers [4]. According to a survey report issued by the International Energy Agency (IEA) in 2013, 99% of the PV systems installed internationally were Grid connected [11]. A modern grid connected PV system has evolved as an active power source that can also perform many complex tasks to support the grid; tasks such as reactive power control, Low Voltage Ride Through (LVRT), voltage and frequency control. The PVDG can serve as an alternative to upgrading the network and its effectiveness can be further enhanced by introducing local energy storage [12]. Recently Germany has invoked new regulations for power conditioning equipment to make them more supportive of grid operation [2]. However, there are multiple problems which may occur due to integration of PVDG units, problems such as over voltage, flicker, harmonics, enhanced losses, phase unbalance, islanding, power fluctuations and frequency variations and more, perhaps yet to be encountered [13]. While the PVDG short circuit current contributions are no longer a problem, due to the use of power electronics in interconnection equipment [14], recent studies have shown that the fault current contribution from inverters may be required for ensuring system stability [2].

III. PV IMPACTS ON DISTRIBUTION SYSTEM VOLTAGES

The load profile of a network has diverse effects on Grid connected PV penetration. In some areas PV peak generation coincides with load peaks especially due to air conditioners in hot weather. The PV peak generation results in distribution loss reduction and overcomes the need for peak load shaving. Obversely, it creates problems of power reversal and hence voltage rise due to low load and high PV generation at noon times (i.e. the hottest time of the day).

The PV penetration level in any power system depends upon multiple factors such as load type and profile, solar irradiance level & cloud conditions, PV concentration along the feeders, network parameters & topology and PV generator connection types (3 or single phase) [15]. The low load and high PV generation results in reverse power flow thus giving rise to the voltage in the LV and MV networks. Another problem is that of reactive power control in the system.

Initially all grid connected PV systems were forced to supply power only at unity power factor, thus injecting only active power, which at certain times disturbed the balance of active and reactive power necessary to keep the voltage within statutory limits. However many studies have now proved the usefulness of providing reactive power through inverters and have recommended changes be made to the provisions in relevant standards [16].

Clouds also play an important role regarding PV penetration limits in a distribution network. The speed of cloud movements is a very sensitive issue, resulting in voltage flickers as the low ramp rates of other generating units in the area will be a limit to supply the power lost due to cloud coverage instantaneously. The frequency of voltage flickers can exceed regulation limits. Flicker is also more likely in an area of densely located PVs.

IV. PV PENETRATION LEVELS AND VOLTAGE VIOLATIONS IN LV NETWORKS

A. DEFINITION OF PENETRATION LIMITS

In the literature there is no single definition of PVDG penetration limits that is unanimously agreed upon. It varies widely among researchers, few of whom have taken it as being simply stated as the ratio of the houses with PV systems to the total houses in the area under study [17]–[23]. We found studies where it was defined as the ratio of roof space utilized for PV installation to the total space available [24] and the ratio of annual energy from PV systems to the total energy consumption [25]. Some researchers have attempted to define it in relation to the transformer capacity [26]–[28] while others have calculated it as the ratio of installed PV peak capacity to the feeder maximum load [12], [29]–[35]. Some have even replaced the ‘‘feeder maximum load’’ with ‘‘feeder minimum load’’ in these ratios [36]–[38] and in [39] and [40] PV penetration at a certain point of time was considered as the ratio of the actual PV output to the actual active power load.

The first three approaches give a broader view of the situation without stating or defining any new or particular electrical parameters, and do not provide any useful technical help in the decision-making process for a Distribution Network Operator (DNO). The transformer capacity-based approach is more relevant to power or current flows in or out of the LV network but it has little significance in regard to voltage.

The over voltage in an LV circuit may occur due to low load and high line impedances, even at very low penetrations of PVDGs, calculated with respect to the transformer capacities. The transformer capacity based approaches however are useful to avoid excess power flows out of the LV network which may cause damage to both conductors and transformers. Thus it can be taken as a secondary limit rather than as the primary limit as upgrading transformers can change the scenario entirely.

The feeder maximum load versus PV peak capacity approach has stronger relevance for both the power flows and the voltage profiles of the network. There are two different scenarios depending on the geographical position and load profile. First, if the peak PV generation coincides with the maximum or peak load then relatively higher levels of PV penetrations will be achievable, however if that is not the case then the network hosting capacity for PVDG will be reduced significantly due to voltage violations. The other approach is feeder minimum load versus PV peak capacity which seems more compatible with the scenarios where peak load occurs at times other than peak PV generation. In this case, feeder minimum load may not necessarily coincide with the peak PV generation thus adversely affecting the true PV hosting capacity of the circuit.

The concept of ''PV peak capacity'' also needs to be understood, given that the actual PV production varies depending upon multiple factors like temperature and solar irradiance. Errors of calculation can occur if only the nominal value of PV peak capacity is considered. A more rational approach is to consider the actual value in particular situations, which vary from region to region depending on the regions' level of solar irradiance and temperature experienced. In strong solar insolation areas temperature tends to be higher, which has the effect of reducing the efficiency of the PV generator, resulting in lower power output from the PV generator. Taking into account both the actual PV generation level and the actual feeder load would allow a more precise scenario for defining the PV penetration limits in LV distribution networks. A more rational approach was considered in [39] and [40] who considered the active current flows and would become more comprehensive if both the active and reactive current flows will be included in calculations.

In addition to the voltage variation, regulations vary from country to country which have a significant effect on estimating PV penetration limits by imposing different voltage variation limits on the network. For example, a ±10% voltage variation limit will enable the network to host more PVs than ±5%, yet the ±5% may be the regulatory limit in that area.

B. PENETRATION LIMITS AT LV IN CONNECTION WITH VOLTAGE CONTROLS

Widen *et al.* [41] reported PVDG impacts with 1-5kW per household installed capacity in three Swedish low voltage Grids. These authors used stochastic modeling for simulations instead of the worst case scenario approach. The energy losses were found to be minimum at 1kW PV penetration per household and no voltage violations were found for any case in all three grids with 1-5 kW PV. This study did not estimate PV percentage penetration but the authors determined that significant PV penetration can be achieved safely if the MV grid is stiff with very low voltage variations.

A campaign was conducted by authors of [26] to measure power quality (in accordance with EN 50160 standard) in 3 different countries of Europe with four different LV grid connected PVDGs (rooftop PV systems) in urban areas. Their report was reviewed by experts with rich experience in the field of Renewable Energy (RE), from different countries. The most important problem reported was voltage violations. The report also established maximum tolerable PV limits. Urban real estate developments with high PV penetrations were selected for impacts measurement. The focus was on network design, maximum permissible capacity of PV, power quality related to standard EN 50160, voltage rise, harmonic current injection from PV and power flow across transformer.

Results showed that high PV penetrations were achievable in urban LV distribution systems. Penetrations of 110%, 80% and 33% PV with respect to transformer capacity were found to be acceptable at three different sites in Germany and Netherlands. The only power quality parameter (under the European Standard EN 50160) that was affected was voltage rise at the end of LV feeders. A maximum of 160 kW of power exported to the MV grid was recorded in the study. Typical urban European LV networks with a PV capacity of 70% of installed transformer capacity is acceptable in general but may be exceeded in some cases. As well, with purpose-made network designs, more PVs can be accommodated by properly designing the capacity of both the transformer and the cables. The reduction in transformer set voltage can accommodate more PVs in the circuit.

Pukhrem *et al.* [28] reported that PV penetration in an LV network can be significantly enhanced (from 35% to 67%) using proposed algorithms designed to control the active and reactive power through the inverters.

An IEA PVPS T5-10 report [29] suggested that PVs should be considered in network planning. For the short term, varying the scheduled changes to the distribution transformer tap was recommended. In the long term, however, the penetration issues could be solved through Demand Side Management. The report also emphasized the benefits of PVs, allowing peak shaving from the load curve, by utilities, at times of air-conditioning peak consumption. PV penetration levels were shown to be reduced with respect to the concentration of PVs along the LV and/or MV network in the neighboring areas. Another important finding was that PVs are not acceptable at minimum load conditions.

Three different voltage control strategies were applied to three scenarios in [24] to raise the LV network PV hosting capacity. The higher penetrations were achieved through the use of reactive power control, active power curtailment and the use of storage systems. The voltage violations were recorded for rural and remote farm cases at comparatively very low penetration levels of 13% and 16% respectively.

In the case of the urban network, there were no voltage-violations recorded, until the thermal limit of network component was reached at a 45% penetration level.

A shorter length (150m) feeder study [38] revealed that a very high percentage (around 500% w.r.t feeder min. load) of PV penetration does not trigger any voltage violations. The primary reasons behind this are likely low impedance of short line and equal distribution of loads with PV generators. It is important to note here that voltage limits are narrow (5%) in this case.

In [36] the impacts of DGs in an urban meshed LV network in Sutton New York were discussed. The results of that study showed that if customers are allowed to install DGs without restrictions, the voltage rise issue occurs between 20-30% of feeder minimum load penetration. However the size of the DG matters even in the cases where a large power DG or cluster of DGs is installed at a certain point in the network. In this situation the voltage rise issue may occur at as low as 2.5% penetration. By contrast, if consumers are restricted to installing DGs equal to their minimum load, 95% penetrations are acceptable. Very similar results have been reported in [37] where 100% PV penetration has produced no voltage violations, however at 135% penetration voltages were out of statuary limits.

A vast urban meshed network (where each transformer was operated radially) having 169 MV/LV transformers was studied by Mohammadi and Mehraeen [31] for three different scenarios of PV integration. PV penetration was considered as the ratio of node maximum load to PV generation. The first scenario has been referred to as "distributed" where 228 PV systems were installed at different nodes. In the second scenario 56 PV systems were installed at nodes with large loads, and in the third scenario 172 PV systems were installed at nodes representing residential loads of less than 200kw. Results showed that PV penetrations between 15%-30%, 45%-60% and 75%-90% were tolerable for scenario 1, 2 and 3 respectively in terms of voltage violations. However there were some cases of cable ampicity violation in all three scenarios.

In [25] a radial real network was modeled in DigSilent Power Factory software with two 630kva MV/LV transformers and 312 customers. Only highly suitable rooftops were considered for PV installation in the area. In this study, PV penetration level was defined as the ratio of the annual energy produced by the PV to the total energy consumed. 43% PV penetration in terms of annual energy production was found to be acceptable without any voltage violations.

In [40] two different case studies were used to run simulations in which Electronic On-Load Tap-Changer (OLTC) equipped transformer was deployed for robust voltage control. When PV was installed at a single point in the network, 20% penetration was found safe. However in the same case the penetration level decreased to around 12% when line impedance was set at 150% of the above case. A 40% penetration did not cause any voltage violation when PV was distributed evenly along the feeder, though it decreased to 30% for higher line impedance.

The results of the study in [17] described a radial network simulation with 50% penetration of PVDGs (in terms of the number of houses) in which no voltage violations were seen, but at 70% and 80% penetrations almost 45% of the network faced overvoltage at the Point of Common Coupling (PCCs) and the PV systems were forced to stop generation until the conditions became normal. A 9 kWh Battery Storage System (BSS) was proposed for each house and it was noted that the 45% figure reduced to 28%, proving that a BSS can be helpful in avoiding the voltage violations up to a reasonable extent.

In a radial LV cable network study [42] it was established that use of BSS can enhance the PV hosting capacity of the LV network by avoiding the voltage rise at peak PV generation hours.

Monte Carlo methodology for simulation of different PV penetration scenarios was used by Procopiou and Ochoa [19] to analyze a real UK rural domestic LV cable network. Simulation showed that there were no voltage violations for 30% PV penetration in the LV network (PV systems were installed in 30% of the houses). An OLTC equipped MV/LV transformer was proposed with a unique control system which used only substation data to raise or lower the tape. Results showed that 50% penetration was acceptable with OLTC equipped transformer for any number of control cycles between 1 to 30 minutes. Lamberti *et al.* [23] used Monte Carlo technique for simulation of a radial domestic network and found that at 30% PV penetration level (30 % houses with PV) the voltage lower limit was violated while the higher limit violation occurred at 50% PV penetration. In [35] also Monte Carlo simulation was used and the authors found that 45% PV penetration against feeder designed load results in no voltage violations in a 315m long radial feeder, where 3 customers were connected at each node (one per phase). There were a total of seven nodes.

A typical rural radial network was studied in [43] where the feeder had 9 equally spaced (50m) nodes. the connected load was 24kW and PV installed capacity was 54kW. Actual loads and PV generation were used for simulation and no voltage violation was found.

Results of simulations using a UK LV network were reported in [32], showing that at 50% PV penetration w.r.t feeder peak load voltage went beyond the statutory limits of 3%. However the minimum acceptable limit was not reported in this study. Another study [22] reported that 30% PV penetration w.r.t total number of houses caused no voltage violations if the power factor of the inverter was kept at 0.92. Moreover 100% penetration was tolerated by the network if an OLTC equipped transformer was used. Hashemi *et al.* [44] found that 45% PV penetration was possible in the network without any voltage violations. One interesting factor here was that all the PV's were at the end of the feeder. The voltage variation limit was 3% in this area.

TABLE 1. **LV network PV penetration limits w.r.t. voltage violations.**

Ref	Max PV %		Limiting factor	Method	Network characteristics	Remarks
	w.r.t TF capacity	w.r.t % load				
[26]	110%	-	Voltage	Actual measurement	Urban radial	-
[26]	80%	-	Voltage	Actual measurement	Urban radial	-
[26]	33%	-	Voltage	Actual measurement	Urban radial	-
[46]	40%	-	Voltage	simulation	Radial	-
[18]	33%	-	Voltage	simulation	Typical urban	-
[28]	35%		Voltage	Simulation	Suburban radial	Domestic cable network
[29]	-	Min load	Voltage	simulation	Radial	-
[36]	-	20-30%of min load	Voltage	simulation	Urban	Random/ small
[36]	-	95%of min. load	Voltage	simulation	Urban	Small distributed DG
[36]	-	2.5% of min. load	Voltage	simulation	Urban	Large DG at one point
[37]	-	100% of min. load	Voltage	Simulation		
[38]	-	500% of min. load	Voltage	Simulation		Voltage gone above limits of 5%.
[40]	-	20% of load	Voltage	Simulation		PVDG at one point
[40]	-	12-14% of load	Voltage	Simulation	PVDG at one point and high line impedance	
[40]	-	40% of load	Voltage	Simulation	Evenly distributed PVDG over the network	
[40]	-	30% of load	Voltage	Simulation	Evenly distributed PVDG over the network and high line impedance	
[31]	-	15-30% of Max,load	Voltage	simulation	Urban	Distributed PV
[31]	-	45-60% of Max. load	Voltage	Simulation	Urban	Large PVDGs

TABLE 1. *(Continued.)* **LV network PV penetration limits w.r.t. voltage violations.**

[31]	-	75-90% of Max.load	Voltage	Simulation	Urban	Domestic
[32]	-	Below 50% of max, load	Voltage	Simulation	Radial	
[34]	-	86% of max. load	Voltage	Simulation		Uneven PV distribution
[35]	-	45% of max. load	Voltage	Simulation	Radial	Shorter length feeder(315m)
[17]	50% w.r.t number of houses		Voltage	simulation	Radial	-
[19]	30% w.r.t number of houses		Voltage	Simulation	Rural radial	Domestic cable network
[20]	150% w.r.t number of houses		Voltage	Simulation		
[22]	30% w,r,t number of houses		Voltage	Simulation		PF was 0.92
[22]	100% w.r.t number of houses		Voltage	Simulation		PF was 0.92 OLTC TF
[23]	30% w.r.t number of houses		Lower voltage limit	Simulation	Radial residential	
[23]	50% w,r,t number of houses		Upper voltage limit	simulation	Radial residential	
[44]	45% w.r.t available capacity		Voltage	Simulation	Radial	PVDGs at the end of feeder
[24]	13% w.r.t availabl r roof space		Voltage	Simulation	Rural	-
[24]	16% w.r.t available roof space		Voltage	Simulation	Remote form	-
[24]	45% w.r.t available roof space		Thermal limit	Simulation	urban	-
[25]	43% w.r.t annual PV energy share		Voltage	Simulation	Radial	-

From the load and PV capacity described in [34] it can be calculated that 86% PV penetration caused no adverse effects on voltages even though the PV was distributed unevenly along the feeder.

Table 1 shows that most of the studies are simulation based, and results are very diverse owing to many reasons such as the definition of PV penetration level (six different approaches can be seen in Table 1) and voltage variation band difference (which varies from 3% to 10%). It is not possible to translate these penetration limits between calculation methods as that would requires additional information which may not be present in all the studies. Hence, it is not possible to evaluate all these results on a single scale. This situation creates a lot of confusion when we discuss the PV penetration levels. It is vitally important to formulate/ a common mechanism to define LV PV penetration levels, so that the variations among the results can be minimized. The voltage rise due to PV penetration in any LV network is very sensitive to the location and size of the PV system. A reasonably large number of PVs can be safely hosted by an LV network if they are distributed evenly over the network in relatively smaller units [36], [40] and [45].

Most of the studies have taken PV interconnection at unity power factor, leaving room for a little more PV hosting if inverters would be allowed to regulate voltage using reactive power [22]. There are many other ways to enhance the PV hosting capacity of LV networks but the scope of this study is limited only to the cases where penetration limits have been defined without applying any voltage regulation measure except the traditional ones, which are already in service.

V. FACTORS AFFECTING PV PENETRATION LEVELS AND RULES OF THUMB

There are no absolute PV penetration limits in LV grids, because it depends upon many and various factors. PV penetration limits need to be studied/investigated and analyzed for local conditions, however rules of thumb based on studies and experiences of a certain set of conditions can be determined and used to facilitate the fast PV integration in the distribution systems. In the USA a 15% PV penetration w.r.t. MV feeder maximum load is considered safe and is allowed without detailed studies for interconnection impacts [47]. The 15% and 20% limits were also determined by [48] and [49] respectively in terms of cloud transients. These limits have been determined for cloud effects on voltages in MV networks with PVDGs in circuit. The presence of other types of DGs or storage systems along the feeder may change these limits. Only downstream power flow from transmission network was considered in the study as an alternate option to the amount of PV power lost in a short time span due to cloud transition. Cloud transition time must be seen as an important factor and limitation.

These limits for an individual LV network within an MV network can be different depending upon multiple factors. Rules of thumb need to be defined for multiple sets of conditions with a wide perspective, so that they can be adopted under varying conditions in all situations, particularly weather related conditions. The load profiles, generation profiles and network configuration may change the levels of penetrations in certain areas. The PVDG can be more grid supportive in hot areas where the air conditioning load coincides with the peak PV power generation [18], thus enabling the network to host more PVs. Also varying voltage regulations have significant effect on the rules of thumb appropriate to local circumstances.

Weather conditions and solar irradiance patterns in Thailand, for example, are somewhat different in terms of seasonal variations, as there is little variation in temperatures over the year. The limits of PV penetration in LV networks thus need to be worked out to support the investment and to help the Distribution Network Operators (DNOs) to provide safe and reliable interconnection of PVDG.

Further studies to investigate the impacts of PV penetration and application of new mitigation techniques suitable for local conditions are essential to facilitate the development of certain rules of thumb for a particular region. Our future work will provide further information on rooftop PV penetration in LV network. This study has already commenced and will concentrate on typical Thai conditions. A report on the results will be prepared in the near future.

VI. CONCLUSION AND RECOMMENDATIONS

The aim of this study was to explore the issues related to PV penetration levels for LV distribution network with an emphasis on voltage variations, reported and discussed in literature. The analysis of different techniques proposed in the literature revealed that, if the relationship between actual load and actual PV generation [39] is included in the calculations, this provides a more comprehensive approach than have been available thus far. Our review further revealed that for the MV distribution networks as a whole, voltage control becomes difficult if the total installed PV capacity exceeds 20%. The major cause of this problem is the inability of the transmission system to instantaneously respond and supply the power lost due to sudden cloud coverage, although power reversal also creates slow voltage violations. The LV network of an individual transformer however has different limits depending on multiple factors. In contrast to the MV level network [47], voltage violations in the LV network can be avoided even at high penetration levels (around 90% of feeder maximum load [31]) in certain conditions. The voltage rise is highly sensitive to the position and concentration of PVs along the feeder. However, it is possible to integrate a large number of PVs without any major changes in the LV network parameters by carefully deciding the size, location and concentration of the PVs along the feeder length. The prime obstacle in absorbing large amounts of PV safely, is the voltage control at the MV level which is more sensitive than at the LV network level. Detailed investigation is required to establish rules of thumb for penetration limits of PV in LV networks using diverse network types and generation profiles worldwide.

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