Impact of High PV Penetration on Voltage Profiles in Residential Neighborhoods

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***Abstract*—The objective of this paper is to provide an assessment on voltage profiles in residential neighborhoods in the presence of photovoltaic (PV) systems. The network was modeled in PSCAD using common feeder characteristics that Canadian system planners use in suburban residential regions. A simulation study was performed to investigate potential voltage rise issues in the network up to 11.25% total PV penetration in the feeder and LV transformer capacity penetration up to 75%. Results indicate that the PV penetration level should not adversely impact the voltage on the grid when the distributed PV resources do not exceed 2.5 kW per household on average on a typical distribution grid. Moreover, the role of feeder impedance, feeder length, and the transformer short circuit resistance in the determination of the voltage rise is quantified.**

***Index Terms*—Grid disturbances, overvoltage, power distribution, power system modeling, power system planning and power quality, solar power generation.**

I. Introduction

REGULATIONS and utility requirements vary between regions and countries. Since many utilities and system regulators have concerns regarding distributed generators (DG) interconnection, partially because of the lack of intensive published studies, they do not feel able to guarantee reliability and quality to other customers once they allow distributed generation to be connected without strict requirements.

An important limiting issue is overvoltage in low voltage (LV) feeders in the presence of non-dispatchable DG units. Due to the stochastic nature of the solar irradiance, photovoltaic (PV) units are considered uncontrollable (non-dispatchable) regarding active power. During high generation and low load periods, there is a possibility of reverse power flow in the LV feeder. Several studies indicate that the voltage will rise when there is reverse power flow in the feeder due to DGs interconnection to the low voltage network [1]–[7]. In general, the voltage limits established for inverter protection (0.88 and 1.1 pu of voltage) are mostly beyond North America's voltage limits for distribution networks (0.917 and 1.042 pu [8], [9]). Thus, the feeder may be experiencing overvoltage while the inverter protection does not reach its threshold value. Such overvoltage cases have been observed in light loaded systems [1], [2] and can limit the amount of PV that can be installed on these feeders. For instance, Germany limits the maximum voltage increase on the LV level due to distributed generation to 0.02 pu [10].

In urban areas, the feasibility of solar-based neighborhoods has been demonstrated in [3], [4]. A detailed US monitoring study for a neighborhood of 115 houses with 2 kW of PV panels and a total capacity of 230 kW [3] did not reveal excessive service or substation voltage due to reverse power flow from exporting PV systems: only a slight voltage rise of approximately 0.6% was observed on clear days. Although the penetration levels on this study may not be considered high, the voltage rise might have a different effect on the system, depending on the feeder characteristics [7].

In [9], several studies of urban real estate developments in Germany, Netherlands and France with high penetration of distributed PV generation were investigated. The voltage level increase was within the tolerance bands required by European standards (0.9 and 1.1 pu [11]). A current network in a city in the U.K., that did not include PV resources, was modeled using a stochastic approach and one-minute data information about house/load consumption and the solar irradiance data obtained for the region [5]. Overvoltages were found in this feeder in the case that included 1.8-kW PV systems in 50% of the 1262 houses.

The stochastic nature of solar energy sources has a significant impact on when overvoltages are likely to happen, in addition to the fact that the generation might be correlated with load. Residential feeders with PV systems can be considered a critical case regarding overvoltage [6]. The typical load profile of residential feeders presents a peak value during night time when there is little or no PV generation. On the other hand, the demand is relatively low when power generation peaks, leading to reverse power flow in the feeder and consequently overvoltage. Conversely, the typical load profiles of commercial and industrial feeders present a good correlation with the typical PV power profile, which tends to reduce the likelihood and magnitude of overvoltages, for the same ratio of peak load and peak power generation. A preliminary simulation assessment is usually performed to investigate the potential issues on DG integration. Thus, it is important in the planning

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stage to consider the minimum load level during daytime and, most importantly, the feeder characteristics to define the limits for PV systems installation in order to avoid overvoltages.

In this context, the main contribution of this paper is to present a residential suburban feeder model implemented in PSCAD which allows the performance of a variety of case studies to evaluate the potential risks of DG integration. In addition, results of a simulation study on the possible impact on the feeder voltage profile with a majority of residences integrating grid-connected PV is presented. The system, consisting of an overhead feeder with a total of 216 houses, is modeled in PSCAD using common feeder characteristics that Canadian system planners use in suburban residential regions.

This study focuses on the impact of high penetration of photovoltaic systems on the voltage profile of a residential suburban neighborhood. The paper is organized such that Section II describes the proposed test feeder and presents the Canadian voltage limits and standards for LV feeders with DG. Section III presents results of a case study investigating the impact on the network voltage profile with high PV penetration. Finally, Section IV presents the conclusion.

II. System Description

This section describes the operational limits regarding steady state voltage on LV networks and the model of the overhead residential suburban feeder. The system, consisting of a overhead feeder with 216 houses, was modeled using common suburban residential feeder characteristics described in [12].

A. Operational Limits of LV Feeders

LV feeders are designed to supply a certain load at a certain distance without considering distributed generation. CAN/CSA-C22.2 No. 257-06 [13] specifies the electrical requirements for the interconnection of inverter-based micro-distributed resource systems with grid-connected low-voltage systems in Canada. This standard recommends using the CAN3-C235 [9] as guidance for appropriate distribution system steady state voltage levels for feeders up to 50 kV. For single phase connection, it is considered normal operating conditions (NR—Normal Range) when the voltage level is within 0.917 and 1.042 pu. On extreme operation conditions, the under and over steady state voltage limits are 0.88 pu and 1.058 pu, respectively. It is worth mentioning that although networks are allowed to operate under extreme conditions (ER), improvement or corrective action should be taken on a planned and programmed basis. In other words, if the voltage in a certain point of the feeder is beyond the NR and within the ER, the utility would need to take a corrective action; however, this action is not urgent. If the voltage is beyond the ER, a corrective action should be taken in an urgent matter. Besides, on CAN3-C235 [9] there is no recommendation of whether a certain amount of occurrences might be acceptable in the feeder. This differs from European standards (i.e. EN 50160), where for 5% of a week, it is acceptable to have occurrences of overvoltages up to a certain magnitude. Most Canadian utilities adopt the CAN3-C235 [9] limit for normal operation (NR), which will be used as reference in this study for planning

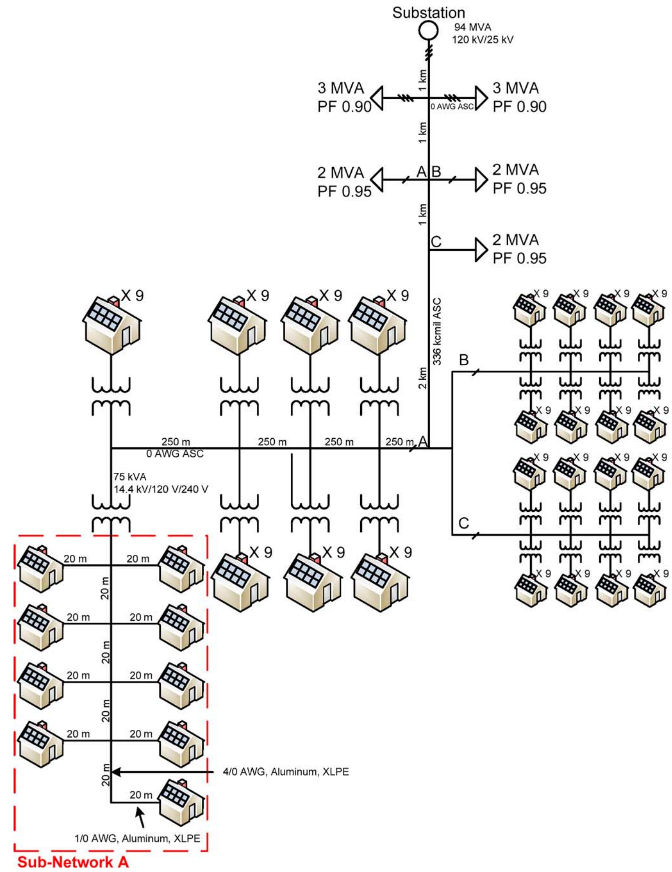

Fig. 1. Overhead residential test feeder configuration.

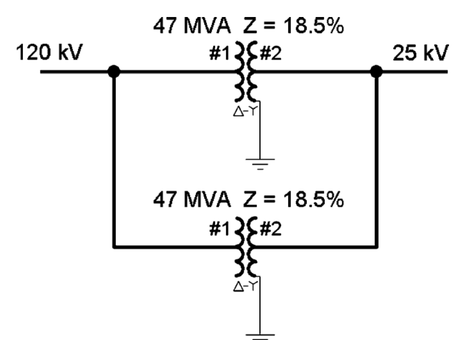

Fig. 2. Substation topology.

the maximum PV capacity per household. Also, it is assumed that planning engineers have access to the information about minimum loading during daytime in the feeder under study and that this might happen at peak generation, which would be the worst case scenario for overvoltage.

CAN/CSA-C22.2 No. 257-06 [13] reveals that voltage regulation is the responsibility of the utility and should not be performed by micro power producers unless in agreement with the utility. Current standards do not allow micro producers to regulate their voltages, even by reactive power generation from the PV inverters during high generation periods. Regulation-wise, it is the utility's concern and responsibility to identify possible solutions. In some cases, a simple tap adjustment at the LV transformer may be enough. In other cases, where the net load/generation varies a lot, other solutions must be considered.

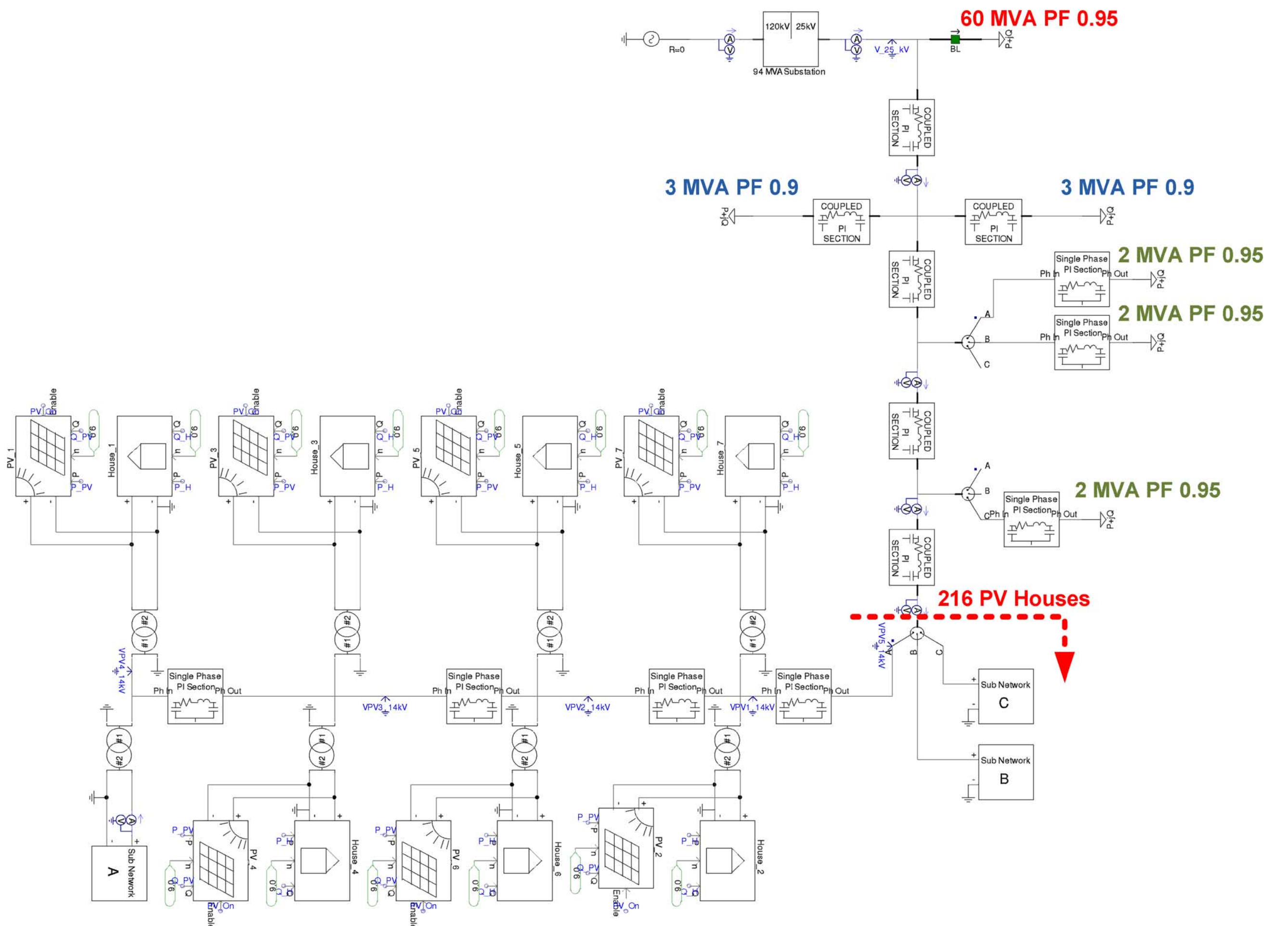

Fig. 3. PSCAD overhead PV neighborhood feeder model.

B. Network Model

1) Overhead Network Configuration: The overhead distribution network was inspired by [12]. It consists of a 100 MVA distribution substation, a residential feeder (test feeder), presented in Fig. 1, and four adjacent feeders represented by an aggregated, constant, balanced load of 60 MVA operating at 0.95 lagging power factor. The substation consists of two 47MVA, delta/wye, 120 kV/25 kV transformers with secondary windings neutral grounded. No capacitor bank is used. Fig. 2 provides an illustration of the basic topology of the substation. The transformers are equipped with an on-load tap changer on the secondary winding $+/-10\%$ voltage variation over 32 steps. The tap changing control strategy is to maintain a fixed voltage at the substation without further line drop compensation. The voltage set point is adjusted to 1.03 pu and the control bandwidth is 2% of the rated voltage.

The overhead neighborhood under study is located at the end of a 5-km, 25-kV overhead feeder (test feeder). The feeder is wired with 336 kcmil, all aluminium stranded conductors (ASC). Along this 5-km feeder, there are distribution laterals wired with 0 AWG ASC as follows:

- At 1 km from the substation: Two 3 MVA, three-phase laterals operating at 0.9 power factor and distributed over 1 km.
- At 2 km from the substation: Two 2 MVA, single-phase (A and B) laterals operating at 0.95 power factor and distributed over 2 km.
- At 3 km from the substation: One 2 MVA, single-phase (C) lateral operating at 0.95 power factor distributed over 2 km.
- At 5 km from the substation: the three-phase feeder is split into three one-phase laterals constituting the neighborhood under investigation. Each lateral has a total length of 1 km and has eight 75 kVA, single-phase, 14.4 kV–120/240 V, evenly distributed transformers (distributed at 0.25-km distances). The secondary circuit of each transformer is 80 m of cable type NS90 consisting of two live wires twisted around a grounded neutral cable. Along this circuit, there are nine customers connected in pair to a splice every 20 m with the last customer connected separately at the end. The service entrance constitutes of two wires supported by a steel grounded neutral cable that has a length of drop of 20 m.

2) PSCAD-Based Network Model: The system consists of 32 houses as presented in Fig. 3. Each house is composed of a PV inverter and a house load model. House groups 1 to 7 are aggregated models, each simulating nine houses. Each of subnetworks B and C consists of eight aggregated house groups. Finally, a detailed model for the house group representing sub-

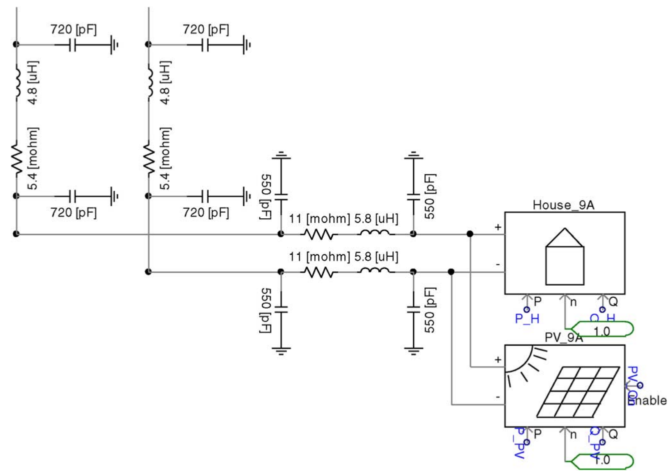

Fig. 4. Detail of the connection to the last house in subnetwork A.

TABLE I
SINGLE-PHASE PI SECTION LINES PARAMETERS (PER LINE CONDUCTOR)

	Drop Lines	Pole-Pole Lines	Laterals
R	0.549 Ω / km	0.27 Ω / km	0.535 Ω / km
L	0.23 mH / km	0.24 mH / km	1.33 mH / km
C	0.055 µF / km	0.072 µF / km	4.3 nF / km

TABLE II
THREE-PHASE PI SECTION LINES PARAMETERS

	336 kcmil Line with 2/0 Neutral ASC	#0 Line with #0 Neutral
R_1	0.1902 Ω / km	0.603 Ω / km
L_1	1.09 mH / km	1.213 mH / km
C_1	11 nF / km	9.90 nF / km
R_0	0.5271 Ω / km	0.978 Ω / km
L_0	3.37 mH / km	3.639 mH / km
C_0	4.9 nF / km	4.73 nF / km

network A is used. Fig. 4 presents the details of the connection to the last house of subnetwork A. All transformers, PI section lines, loads and branches are simulated using standard PSCAD library models. The single-phase lines parameters are given in Table I, and the three-phase PI section line parameters are given in Table II.

The PV inverters and the house models were designed to represent a predefined constant active and reactive power load/generator. Basic inverter protection for voltage trip limits was modeled with respect to Canadian standards [14], [15]. The used voltage disconnection thresholds are 0.88 and 1.1 pu, and the reconnection thresholds are 0.89 and 1.09 pu for undervoltage and overvoltage, respectively. A visual description of the complete PSCAD overhead PV neighborhood system is shown in Fig. 3.

Fig. 5 shows the configuration of the transformer models, and Table III provides the distribution substation and low-voltage transformer parameters.

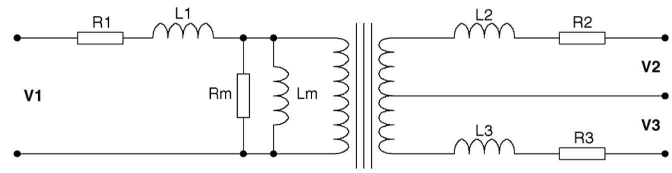

Fig. 5. Transformer model.

TABLE III
TRANSFORMER PARAMETERS

	Low voltage Transformers	Substation Transformer
S	75 kVA	47 MVA
V_1	14.4 kV	120 kV
R_1	0.006 pu	0.005 pu
L_1	0.02 pu	0.0924 pu
$V_{2,3}$	120 V	25 kV
$R_{2,3}$	0.012 pu	0.005 pu
$L_{2,3}$	0.025 pu	0.0924 pu
R_m	500 pu	500 pu
L_m	500 pu	500 pu

III. SIMULATION RESULTS

It is well known that the feeder voltage profile will rise when connecting a unity power factor distributed energy resource to that feeder. This section presents a case study on the impact of high PV penetration on the voltage profile of a residential suburban neighborhood using the proposed network described in the last section. Voltage profiles contemplating a variety of scenarios are presented to investigate the limits of PV penetration as well as the maximum power allowed to be exported guaranteeing adequate voltage levels.

The models were developed to perform a load flow study. The house load behavior could vary with various unaccounted parameters as it is considered a very chaotic load. Indeed, there is no overall control on each consumer's habit and load connections, and therefore no standard can regulate the residential load behavior. Moreover, their behavior depends on so many factors that it is impossible to create a global generic model. Therefore, the house load was considered equal among all the houses for simplification purposes. The PV inverters were ideally modeled as controlled power sources which are considered sufficient for a load profile study. Therefore, in all test cases, only the net load/generation per house was considered. The approach used to identify the maximum PV capacity that could be installed in a certain feeder starts by identifying the maximum net generation possible where overvoltages would not happen. As the maximum net generation is known, planning engineers are aware of how to deal with highly variable loads and how to determine the feeder's minimum load level during the day so that the maximum PV capacity that could be installed in the feeder without having overvoltages can be defined.

Four case studies were investigated. The first case presents the feeder voltage profile considering an average feeder load level and low feeder load level. The second case investigates the effect of LV feeder impedances parameters. The third case studies the LV transformer impedance influence on the voltage

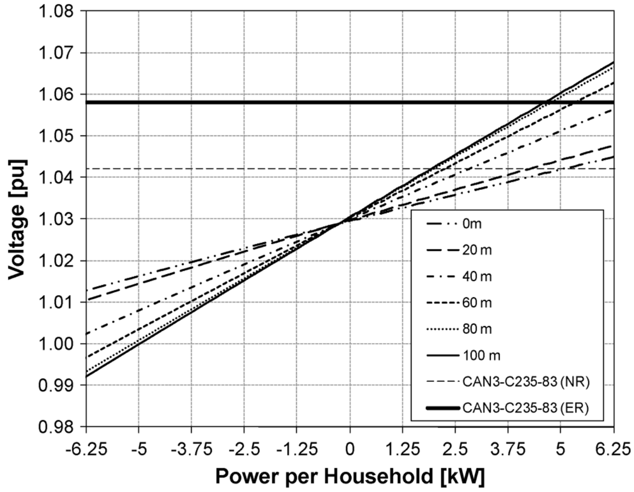

Fig. 6. Voltage profile in the subnetwork A (LV).

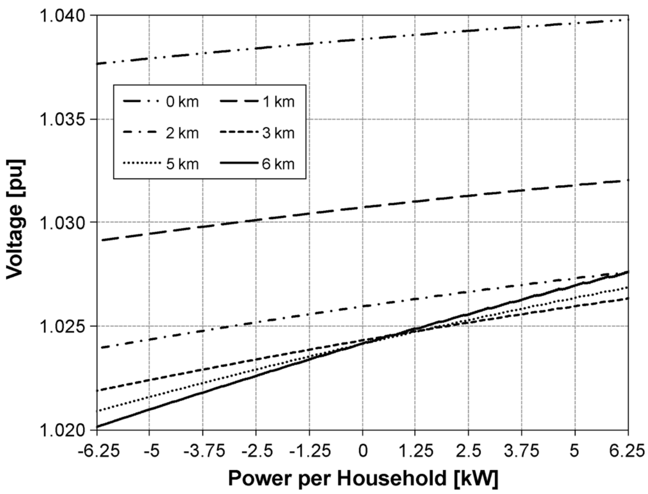

Fig. 7. Voltage profile in the distribution system (MV).

profile. In the fourth case, the impact of different neighborhood feeder layouts is evaluated. Results for the four case studies will be discussed in more detail in the following subsections.

A. Base Case

In this case, the houses' net loading/generation varies between ±6.25 kW (6.25 kW net consumption to 6.25 kW net generation) at unity power factor (UPF). The choice of modeling the residential loads to operate with UPF is based on the worst case scenario. Besides, LV feeders present a higher sensitivity to active power than reactive power [7].

Two scenarios were chosen to define the limits of net generation in the feeder regarding voltage rise. The first scenario investigates the network with a 60 MVA equivalent load, representing the adjacent feeders being connected to the substation. Results of this scenario are presented in Figs. 6 and 7. For net generation levels below 1.93 kW per house, the voltage was within CAN3-C235 [9] limits for normal operation (NR). The voltage rise rate (slope of the voltage trend measured in the graphic) found at the last customer was 0.60%/kW/house.

Fig. 7 presents the corresponding impact on the distribution system voltage profile. The voltage rise rate found in the backbone of the network was 0.059%/kW/house. Also the voltage

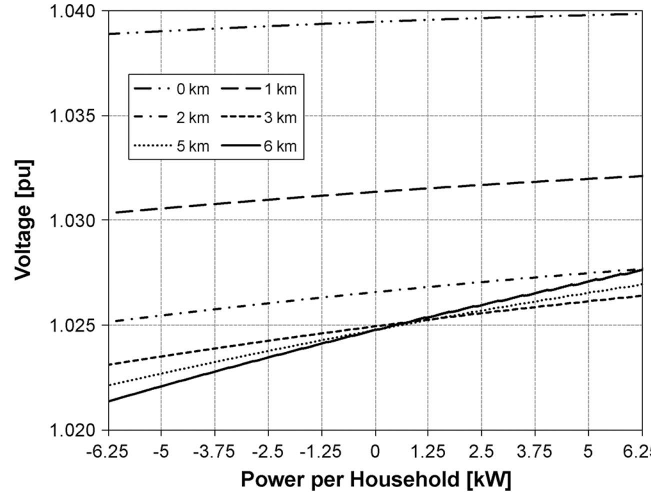

Fig. 8. Voltage profile in the distribution system without the 60-MVA load (MV).

levels were always below 1.04 pu in all parts of the 25 kV distribution feeder. It is important to remark that the voltage in the 25 kV side of the substation is already close to the upper limit of operation of the tap changer. A further increase in the generation would change the tap, so that the voltage in the substation would be kept below 1.04 pu, making this case the worst scenario.

In the second scenario, the 60 MVA equivalent load is disconnected from the network, emulating a period of extremely low loading level in the feeder. The voltage on the secondary network of the distribution transformer rises; however, with the operation of the tap changer, it remains within the appropriate limits as shown in Fig. 8.

The corresponding voltage profiles on the LV transformers' network are presented in Fig. 9. Given the low loading condition, there is a small voltage offset if compared with the first scenario, as the tap changer compensated the new loading condition. Again, it can be seen that the voltage rise rate in the 25 kV distribution feeder is 0.050%/kW/house, which differs from the rate at the last customer of the LV part of the feeder (0.60%/kW/house as well as in the first case). In the LV network, for net generation levels above 1.87 kW per house (∼22% of LV transformer capacity), the voltage level exceeds CAN3-C235 [9] limits for normal operation.

B. Feeder Impedance Effect

Feeder impedance plays an important role to determine the voltage rise in the feeder. To investigate the effect of different feeder characteristics, two situations were studied: One where the absolute value of the feeder impedance varies and the second where the feeder impedance characteristics $(K = R/X_L)$ vary.

Tables IV and V show the line parameters used in the simulations. In these scenarios, the 60 MVA load is disconnected. All the values chosen are based on the typical cables and conductor configuration found in LV feeders. For instance, a two-fold increase in the impedance has a similar effect of using a 1/0 AWG cable in the pole-pole lines of the LV feeder instead of the 4/0 AWG considered the base case, and a 266 kcmil cable has its line impedance about 25% lower than a 4/0 AWG cable. Additionally, the range used in these simulations takes into consid-

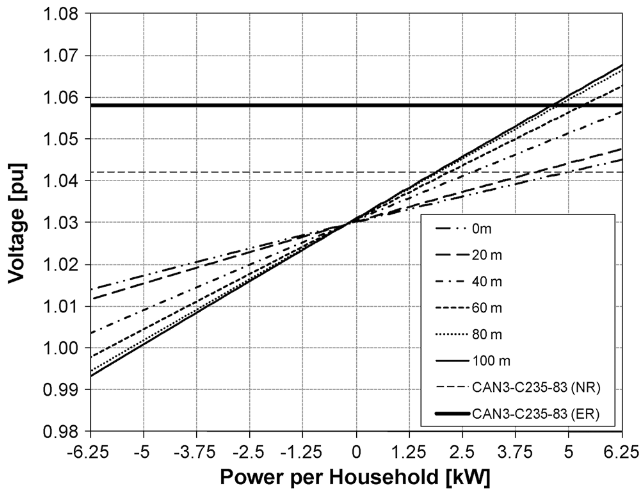

Fig. 9. Voltage Profile in the subnetwork A without the 60 MVA load (LV).

TABLE IV
SINGLE-PHASE PI SECTION LINES PARAMETERS EACH CASE STUDIED SAME K DIFFERENT |Z|

		Drop Lines	Pole-Pole Lines
Z_b (Base Case)	R	0.55 Ω / km	0.27 Ω / km
	L	0.29 mH / km	0.24 mH / km
Z = 2 Z_b	R	1.1 Ω / km	0.54 Ω / km
	L	0.58 mH / km	0.48 mH / km
Z = 1.5 Z_b	R	0.825 Ω / km	0.40 Ω / km
	L	0.43 mH / km	0.36 mH / km
Z = 1.25 Z_b	R	0.68 Ω / km	0.33 Ω / km
	L	0.36 mH / km	0.30 mH / km
Z = 0.75 Z_b	R	0.42 Ω / km	0.20 Ω / km
	L	0.22 mH / km	0.18 mH / km

TABLE V
SINGLE-PHASE PI SECTION LINES PARAMETERS EACH CASE STUDIED SAME |Z| DIFFERENT K

		Drop Lines	Pole-Pole Lines
K_b (Base Case)	R	0.55 Ω / km	0.27 Ω / km
	L	0.29 mH / km	0.24 mH / km
K = 3 K_b	R	0.56 Ω / km	0.283 Ω / km
	L	0.1 mH / km	0.08 mH / km
K = 2 K_b	R	0.558 Ω / km	0.281 Ω / km
	L	0.15 mH / km	0.12 mH / km
K = 0.5 K_b	R	0.521 Ω / km	0.237 Ω / km
	L	0.55 mH / km	0.42 mH / km
K = 0.33 K_b	R	0.482 Ω / km	0.201 Ω / km
	L	0.76 mH / km	0.54 mH / km

eration different conductor configurations like spacing and type of material, which could result in a variety of absolute values of the feeder impedance and feeder impedance characteristics.

Fig. 10 presents the voltage at the last customer while varying the absolute value of the feeder impedance. The feeder experiences a higher voltage rise when the line has a higher impedance. The voltage rise rate for the last customer in the

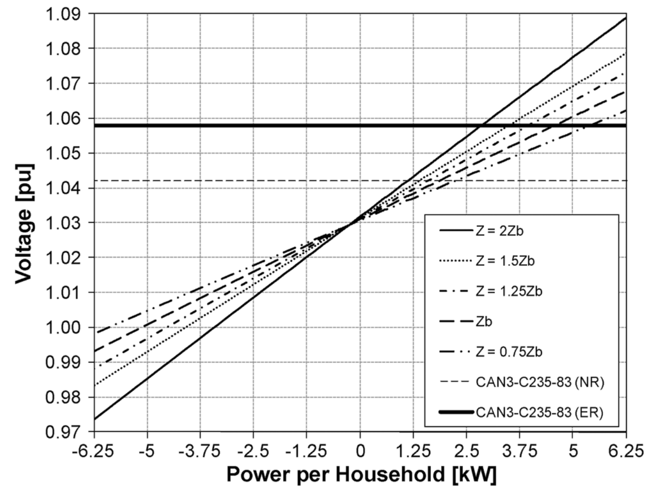

Fig. 10. Voltage level at the last customer node for different LV feeder impedances ($|Z|$) (LV).

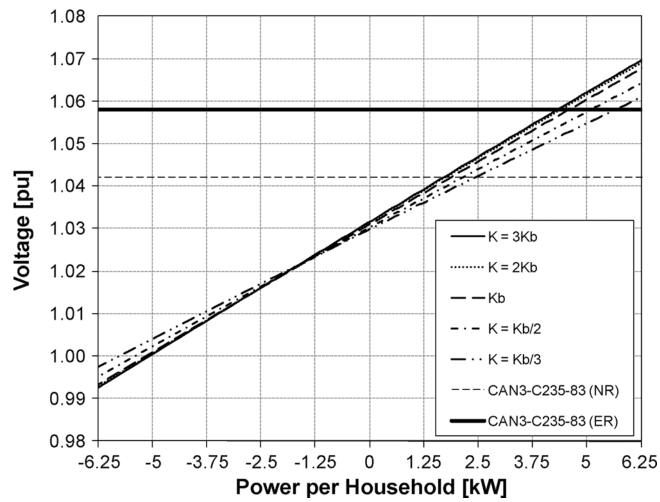

Fig. 11. Voltage level at the last customer node for different LV feeder impedances ratio ($K = R/XL$) (LV).

LV part of the feeder, when the feeder impedance is twice the value used in the base case, was 0.93%/kW/house, which is almost 55% above the base case value (0.60%/kW/house). Also, for lower net generation values, the voltage exceeds the CAN3-C235 [9] NR limits. As a reference, when you double the feeder impedance value, the maximum export limit to avoid exceeding the normal threshold is reduced to 1.10 kW/house, which is about 41% below the maximum export limit for the base case with low load.

Fig. 11 shows the results for the variation of the K ratio. The voltage rise rate is also increased for higher K ratios; however, it has lower impact when compared with the impact of the absolute value of the feeder impedance. When the K ratio of the feeder impedance is tripled, the voltage rise rate was found to be 0.62%/kW/house. Also, the maximum export limit to avoid exceeding the normal threshold is reduced to less than 8% (1.72 kW/house) in the same case.

C. *Transformer Short Circuit Resistance Effect*

The transformer resistance has a significant contribution to the voltage rise in the feeder. To investigate the effect of using transformers with different short circuit resistance R_T,

TABLE VI
MODIFIED TRANSFORMER IMPEDANCE PARAMETERS

R_{Tb} (Base Case)	R_1	0.006 pu
	$R_{2,3}$	0.012 pu
$R_T = 1.5\ R_{Tb}$	R_1	0.009 pu
	$R_{2,3}$	0.018 pu
$R_T = 1.25\ R_{Tb}$	R_1	0.0075 pu
	$R_{2,3}$	0.015 pu
$R_T = 0.75\ R_{Tb}$	R_1	0.0045 pu
	$R_{2,3}$	0.009 pu
$R_T = 0.5\ R_{Tb}$	R_1	0.003 pu
	$R_{2,3}$	0.06 pu
$R_T = 0.25\ R_{Tb}$	R_1	0.0015 pu
	$R_{2,3}$	0.03 pu

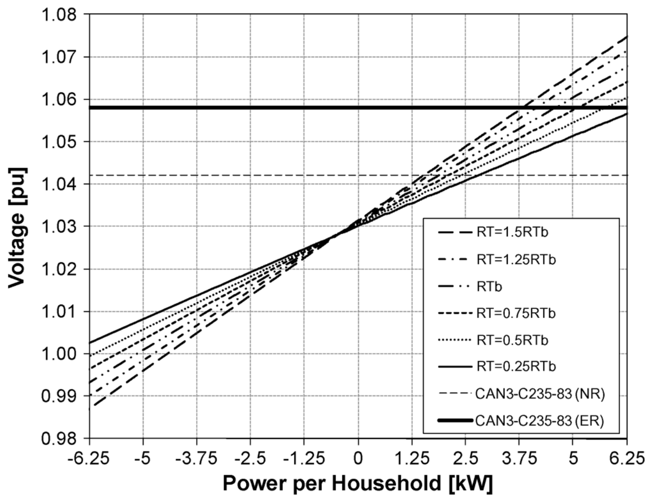

Fig. 12. Voltage in the last customer for transformers with different short circuit impedances (LV).

the 60-MVA load is assumed disconnected and the feeder impedance values are assumed the same as those used for the base case. The parameters modified in the simulation are presented in Table VI. As transformers are mostly custom ordered to meet utilities requirements, the values chosen consider a wide range used by utilities.

Fig. 12 presents the voltage at the last customer. The voltage rise rate is higher when the transformer has larger resistance (0.70%/kW/house). Besides increasing the losses, having transformers with larger short circuit resistance also reduces the capacity of the grid to absorb power. Compared to the base case, for a 50% increase on the transformer resistance, the maximum net generation limit to avoid exceeding the normal threshold is reduced by 20% (1.49 kW/house). On the other hand, if the transformer resistance is reduced by 50%, the capacity is increased by 28% (2.40 kW/house) and the voltage rise rate is reduced to 0.49%/kW/house.

Considering the cumulative effect of using feeders with high feeder impedance values and transformers with high short circuit resistances as the worst case scenario, Fig. 13 presents the corresponding voltage profile to that case. The parameters used to simulate this worst case scenario were: for the LV feeder

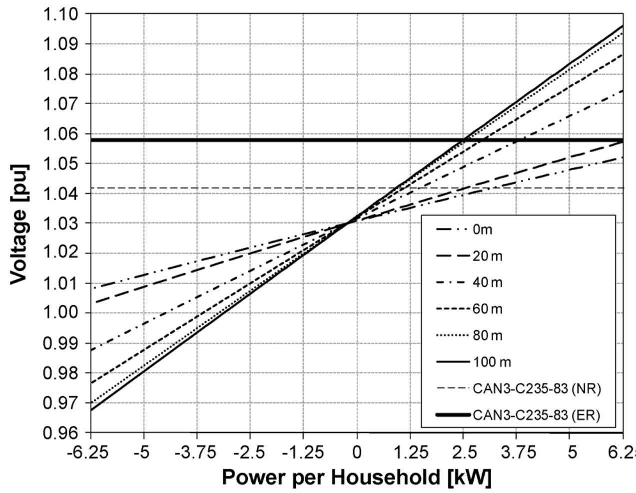

Fig. 13. Voltage profile for the worst case scenario (LV).

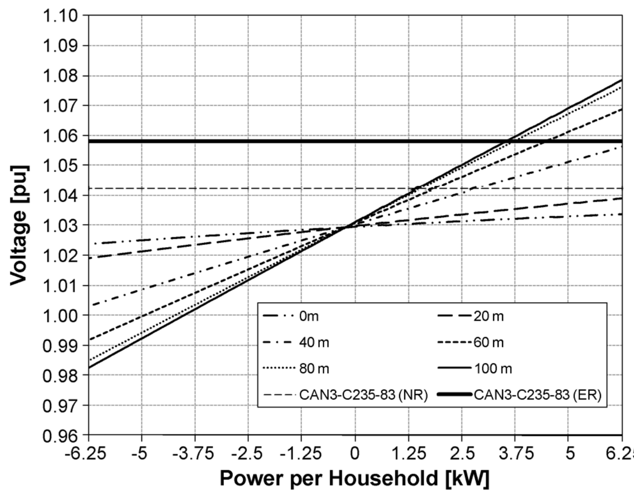

Fig. 14. Voltage profile with transformer with increased efficiency ($Z_T = 0.25Z_{Tb}$) (LV).

impedances, $Z = 2Z_b$ and for the transformer, $R_T = 1.5R_{Tb}$. Results reveal that the export capacity is decreased by 50% (0.93 kW/house) as compared with the base case, and the voltage rise rate is 1.029%/kW/house.

Fig. 14 presents a similar situation, however using the most efficient transformer ($R_T = 0.25R_{Tb}$). In this case, the export capacity is increased to 1.42 kW/house. This means that by reducing the transformer's short circuit resistance and, consequently, increasing the system efficiency, the possibility to experience a voltage rise problem is reduced, thus allowing for the integration of more distributed generation resources into the system. The corresponding voltage rise rate, in this case, was observed to be 0.77%/kW/house.

D. Feeder Layout Effect

The neighborhood layout impacts the feeder impedance values of the network. As the feeder becomes longer, the feeder impedances increase. Fig. 15 shows an alternative layout where the houses are connected in a way that the total LV feeder length is increased from 100 to 180 m. Fig. 16 presents the voltage profile in this neighborhood with a modified layout. When each house is producing 1.04 kW, the NR limit is exceeded. At the

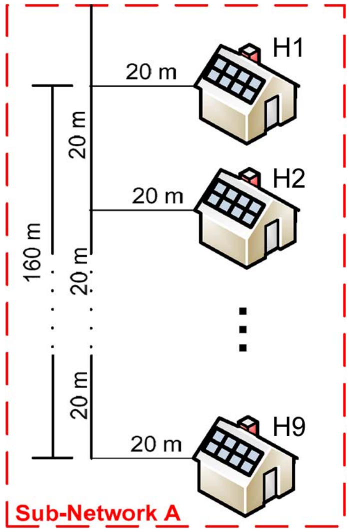

Fig. 15. Subnetwork A modified layout I.

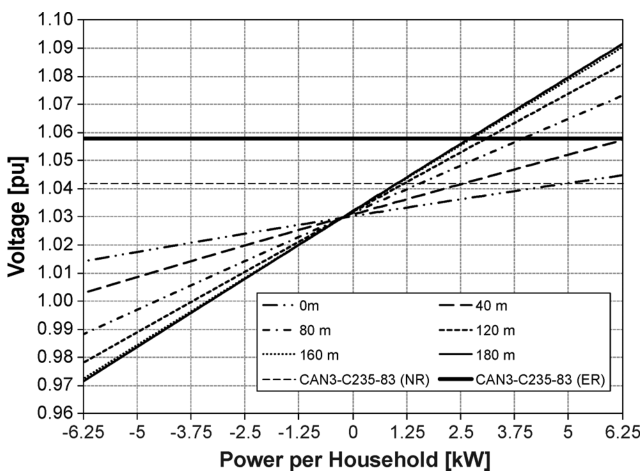

Fig. 16. Voltage profile in the modified subnetwork A (LV).

last house, the voltage rise rate is found to be 0.96%/kW/house.

Rural feeders have longer lines, which increases the feeder impedance values. The concentration of DGs may have a higher impact in this kind of feeder. Therefore, a modified layout of the neighborhood under investigation is simulated considering the rural feeder characteristics as presented in Fig. 17. Each LV transformer feeds 12 houses. The net load/generation is also varied between ±6.25 kW/house. The tap of the LV transformer was adjusted at +5% to avoid undervoltage in the houses during full load condition.

Figs. 18 and 19 present the voltage profile along the subnetwork A for the right and the left feeder laterals, respectively. In this configuration, any slight presence of reverse power flow along the feeder causes the voltage levels to exceed the standard voltage limit for normal operation. At the farthest houses of the left lateral, the voltage rises at a rate of about 2.0%/kW/house (1.6%/kW/house for the last house on the right lateral). This causes the last two PV inverters in the left lateral to trip when the net generation is about 3 kW/house. The voltage still keeps rising until the last inverters from the right lateral houses reach the tripping threshold. This is due to the difference in the house distribution where generation is more concentrated at the end of

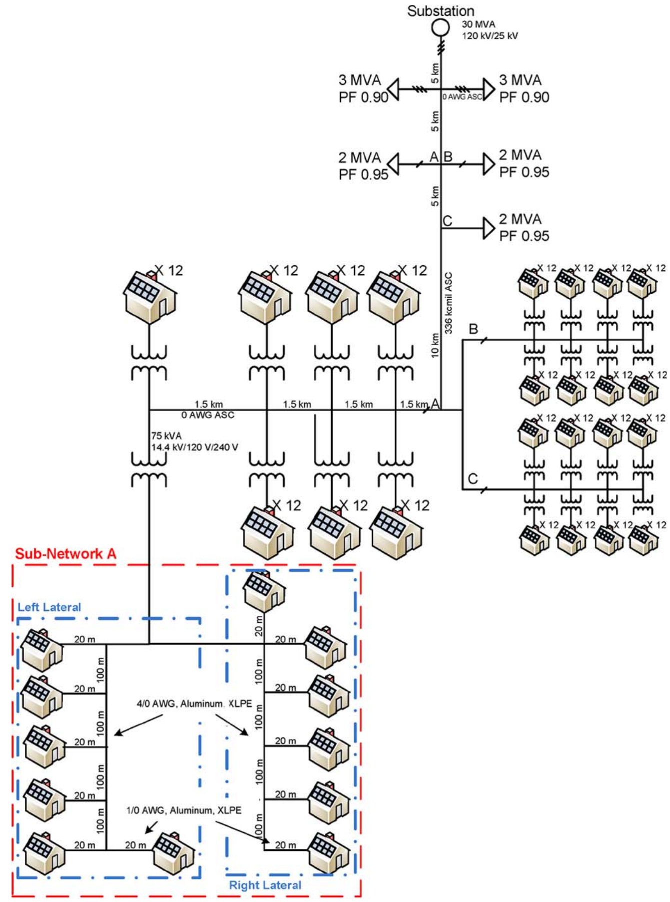

Fig. 17. Rural feeder layout I.

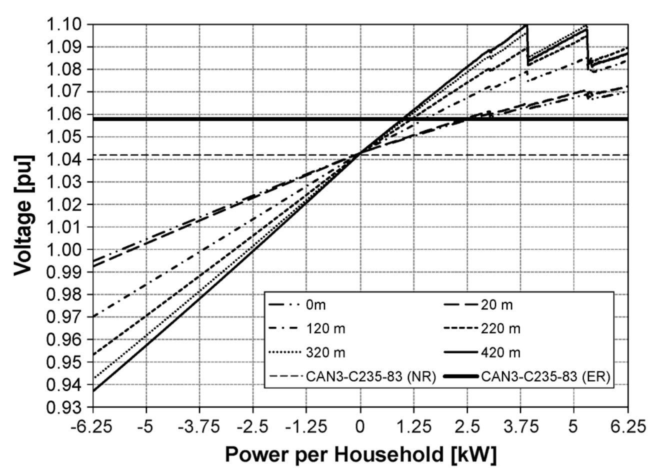

Fig. 18. Voltage profile of the rural feeder in the subnetwork A layout I (right lateral) (LV).

the left lateral, while along the right lateral it is closer to the LV transformer.

Fig. 20 presents the impact on the distribution system. The voltage in the farthest LV transformer varies about 4.5% from full load to full generation conditions in a rate of 0.40%/kW/house, while the voltage levels are within the standard limits.

Another layout for the LV part of the rural feeder is also considered as presented in Fig. 21. The pole-pole lines were modified using a thicker cable (266 kcmil, Aluminum, XLPE) to consider the higher density of the houses in this case.

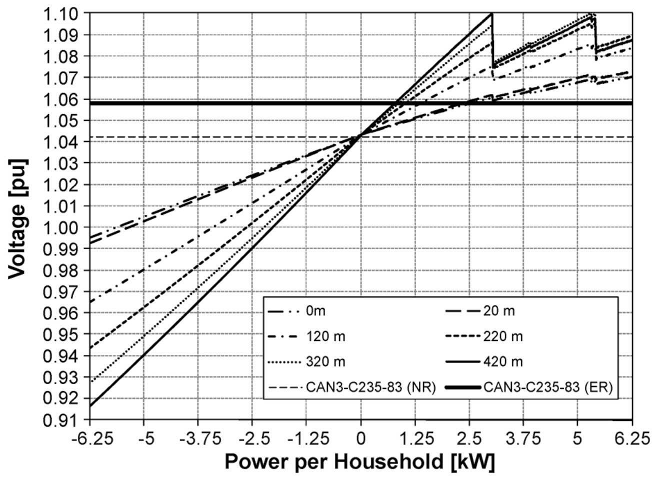

Fig. 19. Voltage profile of the rural feeder in the subnetwork A layout I (left lateral) (LV).

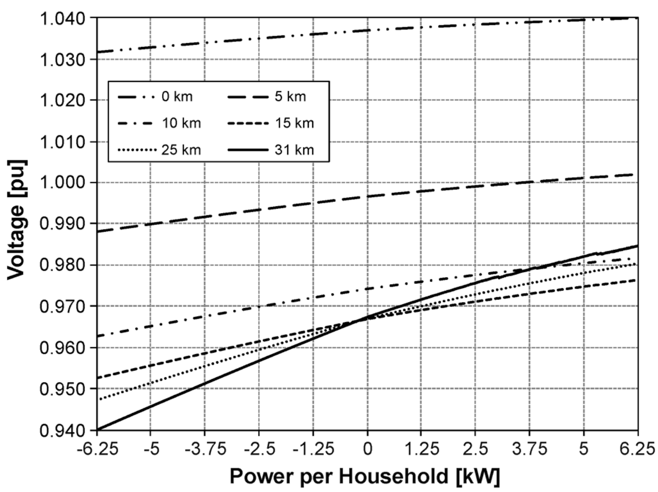

Fig. 20. Voltage profile in the distribution system of the rural feeder (MV).

Fig. 22 presents the voltage profile along the subnetwork A of the rural feeder considering the layout II. In this feeder, with a slight presence of reverse power flow of 0.69 kW/house, the voltage levels along the feeder reach the standard voltage limit for normal operation. At the farthest houses, the voltage rises at a rate of about 1.5%/kW/house. The voltage keeps rising until the last two PV inverters trip, corresponding to net generation of 4.8 kW/house.

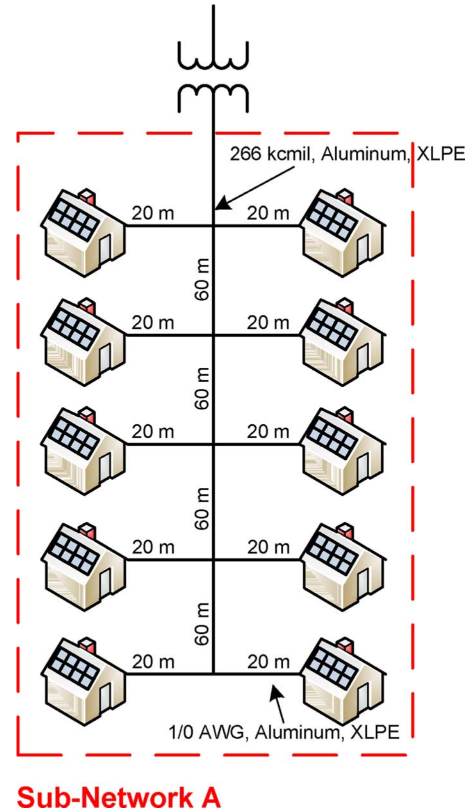

Fig. 21. Subnetwork A layout II rural feeder.

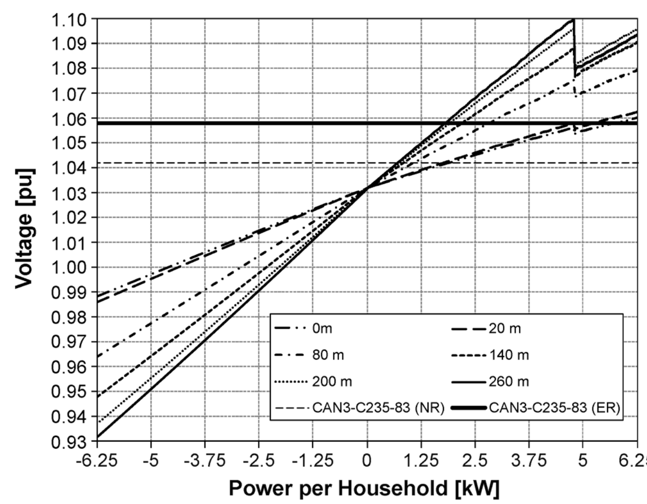

Fig. 22. Voltage profile of the rural feeder in the subnetwork A layout II (LV).

IV. Conclusion

This paper provided an assessment on the voltage profile in residential neighborhoods in the presence of photovoltaic (PV) systems. A residential suburban network implemented in PSCAD was modeled based on common feeder characteristics that system planners use in suburban residential regions as a standard approach. This approach does not consider the integration of DGs into the feeder.

The simulation study revealed that, for overall system PV penetration levels ranging from 0% to 11.25% and up to 75% LV transformer capacity penetration, the feeder impedance, the feeder length and the transformer impedance play important roles in determining the voltage rise rate. Moreover, rural feeders are more likely to experience voltage rise problems because of their long span, which increases the feeder impedance values.

Considering that the residential base load is rarely below 500 W, it can be concluded that an average penetration of around 2.5 kW per household on a typical distribution grid would not push the voltage outside of normal operating range even in the worst case scenarios. Considering the available margin between normal and emergency operation range and load disparity, this conservative number could even be doubled without much concern. A study to evaluate the voltage rise impact considering the particular feeder architecture is recommended for feeders with:

- average installed capacity per household above 5 kW;
- long and/or weak power lines;
- high distribution transformer impedance; or
- a large portion of PV generation concentrated far from the distribution transformer.

Finally, the improvement on LV network efficiency, by reducing transformers short circuit resistance and feeder impedance, would reduce voltage rise issues. Some other techniques that can be employed to mitigate this issue are: to curtail the power of DG units, to store the power surplus for later use, to allow the DGs to absorb reactive power, to reduce the substation tap changer set point or to install auto-transformers/voltage regulators along the line.

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