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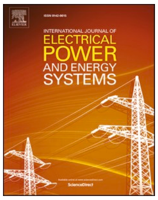

A nomographic tool to assess solar PV hosting capacity constrained by voltage rise in low-voltage distribution networks

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ABSTRACT

Proliferation of solar photovoltaic (PV) generation in low voltage (LV) distribution networks has imposed a set of challenges in network operation and control. Voltage rise is currently the main constraint that limits solar PV capacity increase in LV networks. Together with this, there is a growing need for a generalised and versatile tool which utilities can use to deal with customer requests for new solar PV connections. This paper proposes a generalised approach to assess solar PV hosting capacity (HC) subjected to over-voltage curtailment based on a Nomogram representation, which facilitates reasonable modeling insights for HC assessment in LV networks. In addition, solar PV connection criteria are further developed using the Nomogram representation of HC evaluation. The proposed Nomogram based approach for HC assessment and connection criteria will contribute to further improvement of available guidelines on solar PV connections in LV networks.

1. Introduction

Various incentives have stimulated the integration of solar photovoltaic (PV) systems into low voltage (LV) distribution networks around the world at an increasing rate [1]. As the desire to increase renewable energy grows, solar power generation stands out among other renewable energy resources. Electricity utilities continue to receive a large number of PV connection requests from residential, commercial and industrial customers. Over-penetration of solar PV units challenges the operation of traditional distribution networks, especially when power flow direction is reversed. During periods of higher generation from solar PV compared with lower loading levels further downstream in LV feeders, over-voltages as well as over-loading of conductors and transformers have become evident [2–4]. Thus, distribution network operators (DNOs) are increasingly concerned over the amount of solar PV that can be connected to networks without violating any of the stipulated operating limits, in order to preserve the system integrity.

The concept of hosting capacity (HC) has been introduced to represent the maximum amount of solar PV capacity that can be connected to a distribution network or a feeder, without causing any adverse effects on normal system operations [4–6]. Hosting capacity depends on a number of factors such as the network loading level, feeder/conductor characteristics, solar PV locations and capacity of PV systems [6,7]. Impacts and HC are unique for each network.

The common issues of concern with higher solar PV penetration levels are over-voltage limit violations, thermal over-loading of lines and transformers, voltage unbalance and harmonic distortions in LV distribution networks [7–11]. However, over-voltage is reported as the key factor which leads to curtailment of installed solar PV capacity in LV distribution networks, and it is important to develop useful criteria which facilitate the maximum HC while maintaining network operational constraints within the stipulated limits [7,8,12].

Approaches to assess solar PV HC have been discussed in literature under several aspects, using deterministic and stochastic/probabilistic methods [9,13–18]. In [13], a stochastic approach has been applied to determine the PV hosting capacity at feeder level for four voltage quality criteria: over-voltage, voltage deviation, dynamic voltage drop, and voltage unbalance, specifying a unique solar PV HC for different performance criteria. However, over-voltages caused by high solar PV penetration levels is the most common constraint, and [7,9] provide clear evidence of over-voltage conditions in LV distribution feeders during peak PV generation by means of field measurements. For instance, [14,15] use voltage rise as the performance criterion for solar PV HC evaluation using stochastic analysis methods. Deterministic

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methods are developed in [16–18] to estimate the solar PV HC in LV distribution networks constrained by voltage rise. However, the accuracy of solar PV HC calculated in these studies depends on the number of simulations and complexity of the network model. Furthermore, proposed approaches using deterministic methods in literature can only be applied to a given location at a time and are incapable of capturing all performance criteria for hosing capacity. On the whole these studies are focused on representative or specific network configurations where problems have been experienced and hence give case-specific HC values, and are of limited applicability to practical networks in general. Further, there is a lack of knowledge on generalisation of solar PV HC assessment to incorporate the topological and electrical parameters of different types of networks.

Methods widely used by most of electricity distribution companies for preliminary HC assessment and their rules of thumb for solar PV connections are presented in [19] which are mainly based on the percentage of the peak load of the feeder, percentage of transformer rating and thermal limits of the affected feeders. However, adopting a fixed HC value based on a percentage of a load/transformer/feeder rating for networks or feeders is ineffective as the approach does not address PV locational impact or individual feeder characteristics.

Electricity utilities around the world seek to develop strategies to increase solar PV integration while maintaining the acceptable network performance. There are certain solar PV HC enhancement approaches inclusive of network reinforcement, smart inverter technologies, battery energy storage systems (BESS) and on-load tap changing (OLTC) transformers which are currently available for DNOs [20–23]. However, there is a requirement for generalised and adaptable solar PV connection criteria which include straightforward methodology to assess the solar PV HC without violating network operational limits.

In this paper, a systematic approach is proposed to evaluate the solar PV hosting capacity in LV distribution networks for curtailment owing to over-voltage extending the deterministic outcomes published in [24], further considering the locational variation of solar PV systems. Solar PV HC value will be determined using a Nomogram which is a graphical representation, specific to all locations of a given conductor. This paper further proposes solar PV connection criteria which permits the electricity utility to approve new solar PV connections which facilitates reasonable modeling insights for HC assessment in LV networks. The proposed HC assessment and solar PV connection criteria cover technical and regulatory aspects to tackle PV integration in LV distribution networks. Moreover, the approach proposed in this paper will be a harmonised solar PV HC assessment method for LV networks which helps PV technologies to become more unified and marketed in all countries.

This paper is organised as follows: Section 2 reviews the concepts and current developments of solar PV HC assessment in distribution networks and presents a summary of the deterministic approach on HC based on voltage rise constraint covered in [24][1]. Section 3 discusses the theoretical basis of developing HC Nomograms and Section 4 is a detailed discussion of the proposed methodology to evaluate solar PV HC and solar PV connection criteria in LV distribution networks. Section 5 provides a set of conclusions derived from the study.

2. Solar PV Hosting Capacity

The concept of HC is imperatively a novel solution being sought to enable networks to cope with future developments that can host solar PV penetration, while enhancing reliability and quality of power supply.

2.1. Review of Evaluation of Solar PV Hosting Capacity

The concept of HC for solar PV integration has been defined based on an appropriate performance index or indices subjected to well-defined operational criteria or limits [3,5]. Appropriate power quality indices chosen as performance indices include; voltage rise, voltage unbalance and thermal over-loading of lines and transformers while complying with the operational limits of the network [3,19]. However, uncertainty in solar PV HC calculations may arise due to many factors such as unknown PV locations and their rating, the intermittent nature of their power output, load variations and feeder characteristics [7].

Solar PV hosting capacity assessment in low-voltage distribution networks has been facilitated using both deterministic and stochastic/probabilistic methods. Deterministic methods are typically based on traditional power flow analysis, while stochastic methods include randomness in the solar PV size, location and uncertainties in solar PV power generation and variations in customer load. Furthermore, a comprehensive review [3] of impact studies states that voltage rise and loading of feeders and transformers are the most influential performance indices used in both stochastic and deterministic methods to assess solar PV HC.

Monte Carlo Simulations are used in the stochastic HC assessment approach, which accommodate uncertainties in the solar PV generation and load variations [14]. Studies presented in [7,12] assess power quality issues of increasing solar penetration levels in a practical urban low-voltage network and the limiting factor for solar PV deployments is identified as over-voltages in feeders. In [7], a stochastic method has been developed to assess maximum connectable solar PV capacity in LV networks for over-voltage curtailment. This study reveals factors on which solar PV hosting capacity depends; location of solar PV, feeder loading levels, feeder length and conductor type, and identifies complexity in evaluating solar PV HC using stochastic methods. The study presented in [7] proposes a novel concept of feeder-based hosting capacity approach. Accordingly, for a given feeder, the minimum hosting capacity (safe limit) is the maximum connectable solar PV capacity at the end of the feeder and for a multi feeder network, it is the lowest of minimum hosting capacity of all feeders. For a given feeder, the maximum hosting capacity is the maximum connectable solar PV capacity at the front of the feeder, while maximum hosting capacity of a multi feeder network is the summation of maximum hosting capacities of all individual feeders.

The accuracy of solar PV HC obtained from the traditional Monte Carlo method used in stochastic evaluation of HC depends significantly on the number of simulations and complexity of the network model. In addition, combining performance indices and operational limits in one model in a stochastic method brings out additional challenges that have not been addressed so far.

Furthermore, quick and time conservative deterministic methods have been developed to limit connected solar PV capacity in LV distribution networks, which can account for limitations and diversity of LV networks. Deterministic methods use traditional power flow analysis tools where active power (P), reactive power (Q), conductor impedance (Z) and load models are used as input data [3]. Applying known and fixed input data to a model to analyse the impact of solar PV units in a low-voltage distribution network is a rule-based analysis and hence easy to generalise and such a generalised deterministic method based on feeder level is proposed in [24] for HC assessment constrained by over-voltage highlighting that the solar PV hosting capacity depends on the following uncertainties; location and size of PV systems, feeder characteristics, demand on the feeder, voltage at the distribution transformer and stipulated voltage limits on the feeder. A deterministic method is proposed in [25] considering ampacity to assess the maximum solar PV capacity for a feeder without exceeding feeder thermal limits.

In considering practical aspects, DNOs presently use rules of thumb to quantify solar PV HC, such as, the percentage of the peak load of the feeder, percentage of transformer rating and thermal limit of the

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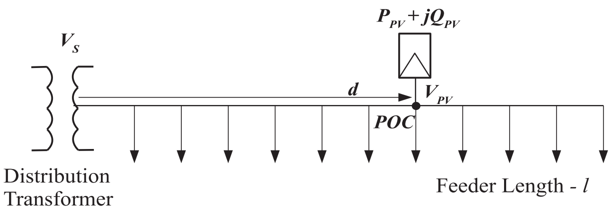

Fig. 1. Distribution feeder model with solar PV.

affected feeders [6]. However, such simple practices and rules of thumb do not address the locational impact of PV and other factors that determine solar PV HC. On the whole, the deterministic approaches proposed in the literature to assess solar PV HC are not simple practices for DNOs to adopt. Hence, DNOs are looking for generalised systematic approaches for solar PV HC evaluation constrained by over-voltage, which possess a close representation of the overall network configuration including topological and electrical parameters. Noting that requirement, this paper extends the deterministic approach presented in [24][2] to form a generalised and systematic solar PV HC evaluation method which can still be used as a rule of thumb to evaluate solar PV HC without using complex stochastic and deterministic techniques.

2.2. *Deterministic Study on Solar PV HC Assessment Subjected to Over-Voltage Curtailment [24]*

The deterministic approach developed in [24] which can be used to evaluate the solar PV HC at a given point on an LV feeder has been utilised to develop the Nomogram based solar PV HC assessment tool. Thus, key findings of the deterministic study on solar PV HC subjected to over-voltage curtailment is summarised as a precursor.

The proposed approach is based on three different models for unity, leading and lagging power factor conditions of PV inverter operation. Furthermore, this approach addresses uncertainties associated with location of solar PV units and loading level along the feeder.

Suppose that a solar PV generator is installed at a distance d from the distribution transformer in a feeder with a length l, as shown in Fig. 1. Let P_{PV} and Q_{PV} be the real and reactive power output of the PV system. The resistance and reactance of the line are R and X in Ohm per unit length, respectively, and the shunt capacitance is neglected. V_S is the supply voltage at the secondary of the transformer and V_{PV} is the voltage at the point of connection (POC).

For unity power factor operation of solar PV inverter ($Q_{PV}=0$), the maximum connectable solar capacity; P_{PV} in the three phases at a distance d from the distribution transformer can be formulated as given in (1).

$$P_{PV}=\frac{V_b^2}{Rd}\left\{(V_{PV}-V_S)+\left(2\lambda-\lambda^2\right)\Delta V\right\} \tag{1}$$

where λ is the d/l, V_b is the nominal line-line voltage and ΔV is the total voltage drop caused by the customer load along the feeder.

Here, V_{PV}, V_S and ΔV are in p.u. and the phase angle deviation between the voltages V_{PV} and V_S is neglected. For maximum connectable PV calculation, the voltage at the POC; V_{PV} should be maximised at the value of upper voltage limit stipulated by the utilities.

For leading power factor operation of solar PV inverter, the maximum connectable solar capacity; P_{PV} in the three phases at a distance d from the distribution transformer can be formulated as given in (2).

$$P_{PV}=\frac{V_b^2}{d\left(R+X\tan\left(\cos^{-1}\left(pf_{pv}\right)\right)\right)}\left\{(V_{PV}-V_S)+\left(2\lambda-\lambda^2\right)\Delta V\right\} \tag{2}$$

where, pf_{pv} is the inverter operating power factor.

For lagging power factor operation of solar PV inverter, the maximum connectable solar capacity; P_{PV} in the three phases at a distance d from the distribution transformer can be formulated as given in (3).

$$P_{PV}=\frac{V_b^2}{d\left(R-X\tan\left(\cos^{-1}\left(pf_{pv}\right)\right)\right)}\left\{(V_{PV}-V_S)+\left(2\lambda-\lambda^2\right)\Delta V\right\} \tag{3}$$

For a given feeder, the safe limit (minimum HC) can be calculated when $d=l$ while the maximum hosting capacity can be calculated by substituting $d=0$.

Eq. (1) depicts a realistic condition, where majority of the solar PV systems in LV networks operate at unity power factor. Hence, the specific results given by the mathematical model presented in (1) can be built into a Nomogram that can be used to develop solar PV connection criteria in LV distribution networks as presented in this paper.

3. Nomogram Based Solar PV Hosting Capacity Assessment

A Nomogram is a diagram representing the relationships between an objective function and variables, by means of a simple graphical construction [26]. Nomograms, consisting of different graduated lines or curves representing given variables, are versatile tools for obtaining solutions for complicated formulae thus providing several advantages. In addition to it being a graphical tool it helps to visualise the outcomes of the formulation in the entire solution space impacted by all variables. Specific theoretical aspects of Nomogram development are given in Appendix A.

The deterministic method of solar PV HC assessment [24] which was summarised in Section 2.2 is formulated as the objective function of the problem, aiming at calculation of maximum solar PV capacity that can be connected to an LV network, under over-voltage constraint. Mathematical formulation of the problem is presented in the following section.

3.1. *Formulation of a Nomogram for Hosting Capacity Assessment*

Based on the outcomes of the deterministic approach [24], this section explores the development of a Nomogram for the case of unity power factor operation.

For a given conductor type and a given feeder length, (1) can be rewritten as (4).

$$P_{PV}-(K_1-K_2d)\Delta V-\frac{K_3}{d}=0 \tag{4}$$

where $K_1=\frac{2V_b^2}{Rl*10^3}$, $K_2=\frac{V_b^2}{Rl^2\ *10^3}$ and $K_3=\frac{V_b^2(V_{PV}-V_S)}{R*\ 10^3}$. Here, solar PV hosting capacity is stated in kW while K_1, K_2 and K_3 are constants for a given feeder.

Eq. (4) represents a formula of a Class-III (see Appendix A for the Class definition of a formula) comprising three variables; solar PV capacity (P_{PV}), initial voltage drop (ΔV) and distance to POC (d). To form the basic determinant for the Nomogram, take $x=-P_{PV}$ and $y=-\Delta V$. Then, (5)–(7) can be obtained.

$$x+P_{PV}=0 \tag{5}$$

$$y+\Delta V=0 \tag{6}$$

$$-x+(K_1-K_2d)*y-\frac{K_3}{d}=0 \tag{7}$$

Since, (5)–(7) are simultaneously true, the absolute value of the

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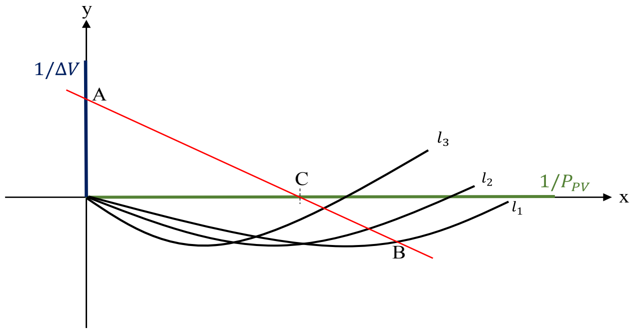


Fig. 2. Nomogram representation of HC.

following determinant is zero.

$$\begin{vmatrix} 1 & 0 & P_{PV} \\ 0 & 1 & \Delta V \\ -1 & (K_1 - K_2 d) & -\dfrac{K_3}{d} \end{vmatrix} = 0 \tag{8}$$

Eq. (8) can be transformed into the basic determinant form of a Nomogram by performing row operations as follows;
$R_1 \leftarrow R_1/P_{PV}, R_2 \leftarrow R_2/\Delta V$ and $R_3 \leftarrow R_3 \ * (-d/K_3)$,

$$\begin{vmatrix} 1/P_{PV} & 0 & 1 \\ 0 & 1/\Delta V & 1 \\ d/K_3 & -(K_1 - K_2 d) * d/K_3 & 1 \end{vmatrix} = 0 \tag{9}$$

where, K_1 and K_2 depend on the feeder length, l for a given conductor type. Loci of the variables, P_{PV} and ΔV are two straight lines which are coincident with x-axis and y-axis respectively ($(1/P_{PV}, 0)$ and $(0, 1/\Delta V)$). Locus of the variable, d is a parabola represented in (10), which is developed using the $(d/K_3, \ -(K_1 - K_2 d) * \ d/K_3)$ co-ordinates.

$$y = K_2 K_3 x^2 - K_1 x \tag{10}$$

As K_1 and K_2 depend only on the feeder length for a given conductor (constant R and V_b for a given conductor), a set of curves can be obtained by varying feeder lengths as illustrated in Fig. 2.

Accordingly, a complete Nomogram for HC evaluation is illustrated in Fig. 2. When $\Delta V, l$ and d are known for a given feeder, solar PV hosting capacity, P_{PV} at the distance of d can be obtained by drawing a straight line connecting the known points; A $(0, \ 1/\Delta V)$ and B $(d/K_3, -(K_1 - K_2 d) * \ d/K_3)$ as shown in Fig. 2 for a feeder of length l_1. The intersection of line AB and x-axis; i.e. point C (given in Fig. 2) represents the reciprocal of solar PV hosting capacity at a distance d from the distribution transformer, $1/P_{PV}$.

Nomogram gives solutions that are valid for a set of conditions or variables and thus, one can easily visualise the impact of change in one variable or condition on another variable. With regard to the new Nomographic tool developed, the loading level, feeder length and the location of the solar PV system are the set of variables applicable to solar PV HC evaluation. Accordingly, Fig. 2 can be used to evaluate the solar PV HC for different conditions such as; (a) change the PV location towards the feeder end, then, the point C moves right hand side along the x-axis resulting lower solar PV HC, (b) increase the loading level (increase the ΔV) results in moving point C towards left hand side along x-axis giving higher solar PV HC and (c) change the feeder length, the point C moves depending on the distance to POC resulting higher or lower solar PV HC.

Furthermore, it should be noted that a given Nomogram is developed for a specific type of conductor. Types of conductor used in LV distribution networks are limited. A utility needs to have one Nomogram for each type of conductor. Therefore, the Nomogram approach provides a practical tool to meet day-to-day utility requirements.

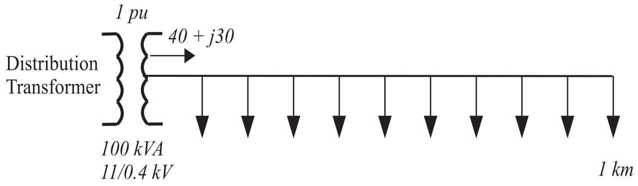


Fig. 3. Test network for a single distribution feeder.

Table 1
Details of the Test Feeders.

Conductor types	R (Ω/km)	X (Ω/km)
3 Phase All Aluminum Conductor		
Type: Fly	0.4505	0.292
3 Phase Aerial Bundle Cable		
Type: $3 \times 70\ mm^2 + 54\ mm^2$	0.441	0.08
3 Phase Aerial Bundle Cable		
Type: $3 \times 50\ mm^2 + 54\ mm^2$	0.641	0.08

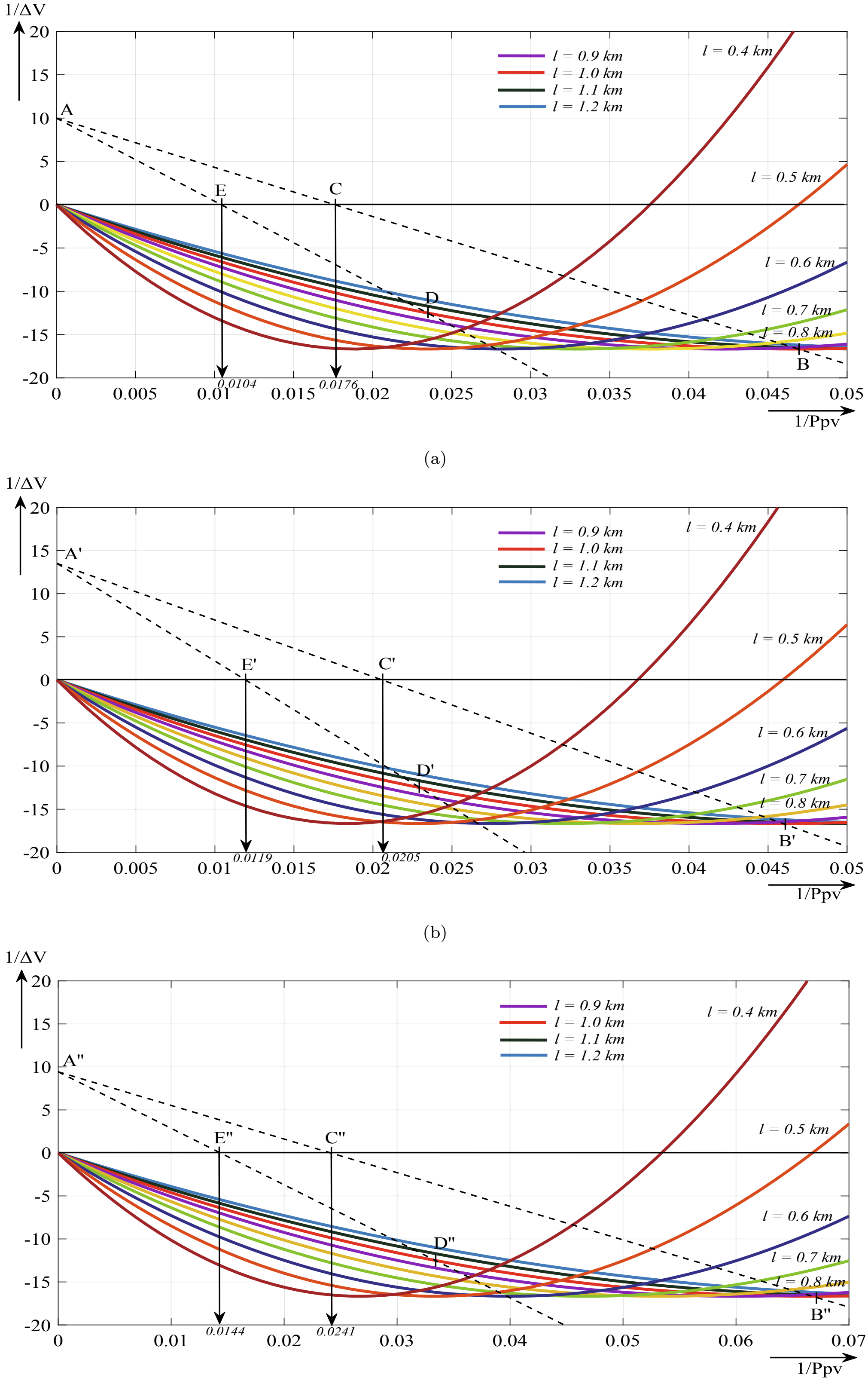
3.2. Assessment of Solar PV Hosting Capacity in an LV Distribution Feeder

The proposed Nomogram approach for HC assessment was verified using simulations developed in DIgSILENT PowerFactory software for a single feeder distribution test network. The test network is served by a 100 kVA, 11 kV/0.4 kV three phase transformer connected to a 1 km long feeder, as shown in Fig. 3. This is the same model used in [24] for the validation of deterministic models. The total midday peak demand on the feeder was assumed to be (P_S and Q_S) 40 kW and 30 kVAr (50% of the transformer capacity). The load was assumed to be balanced and uniformly distributed among 10 nodes along the feeder. Further, the secondary voltage of the transformer, V_S was assumed to be constant at 1 p.u. Three different conductor types; $AAC - Fly, ABC - 70mm^2$ and $ABC - 50mm^2$ were selected for evaluation of maximum connectable solar PV capacity constrained by the stipulated upper voltage limit of 1.06 p.u. at two different locations; feeder end and middle of the feeder. Table 1 gives feeder specifications for selected conductor types.

Nomograms for HC assessment developed for three types of conductor; $AAC - Fly, ABC - 70mm^2$ and $ABC - 50mm^2$ and shown in Figs. 4(a), 4(b) and 4(c) respectively. Furthermore, these Nomograms were developed for solar PV hosting capacity constrained by the upper voltage limit of 1.06 p.u. (+6%).

Calculations to develop Nomogram-based solar PV hosting capacity at the feeder end and middle for the test network used the following steps;

- **Step 1:** determine K_1, K_2 and K_3 for a given conductor and a given feeder length
- **Step 2:** - determine points A and B (given in Fig. 4(a)) for HC calculation at feeder end of AAC-Fly conductor from known system parameters; $\Delta V, d$ and l (determine A' and B' or A'' and B'' which are given in Fig. 4(b) and Fig. 4(c) for ABC-70 mm^2 and ABC-50 mm^2 conductors, respectively)- determine points A and D (given in Fig. 4 (a)) for HC calculation at feeder middle of AAC-Fly conductor from known system parameters; $\Delta V, d$ and l (determine A' and D' or A'' and D'' which are given in Fig. 4(b) and Fig. 4(c) for ABC-70 mm^2 and ABC-50 mm^2 conductors, respectively)
- **Step 3:** - draw a straight line through the points A and B (A' and B' or A'' and B'') which results in the value of point C (given in Fig. 4(a)), corresponding to the reciprocal of solar PV HC at the feeder end of AAC-Fly conductor (determine C' or C'' which are given in Fig. 4(b) and Fig. 4(c) for ABC-70 mm^2 and ABC-50 mm^2 conductors, respectively)- draw a line through the points A and D (A' and D' or A'' and



(a)

(b)

(c)

Fig. 4. Solar PV hosting capacity Nomogram for different types of conductors (a). AAC-Fly, (b). ABC-70 mm^2 and (c). ABC-50 mm^2.

Table 2
Maximum connectable solar PV capacity at the feeder end.

	Simulated (kW) [24]	Deterministic (kW) [24]	Nomogram (kW)
AAC - Fly	58	57	56.8
ABC - 70 mm^2	49	49	48.8
ABC - 50 mm^2	41	41	41.5

Table 3
Maximum connectable solar PV capacity at the feeder middle.

	Simulated (kW) [24]	Deterministic (kW) [24]	Nomogram (kW)
AAC - Fly	96	96	96.2
ABC - 70 mm^2	84	84	84
ABC - 50 mm^2	69	69	69.4

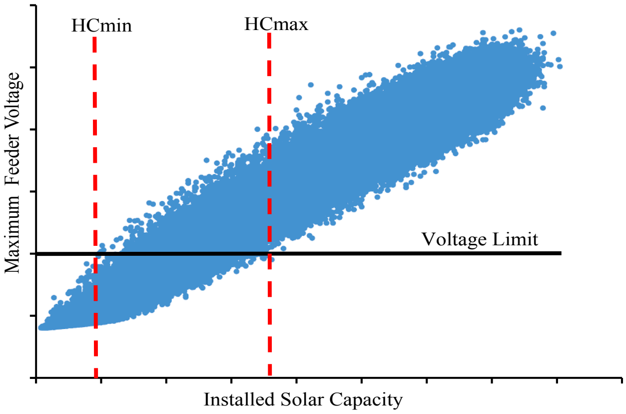


Fig. 5. Two levels of hosting capacity [7].

D″) which results in the value of point E (given in Fig. 4(a)), corresponding to the reciprocal of solar PV HC at the feeder middle for AAC-Fly conductor (determine E′ or E″ which are given in Fig. 4(b) and Fig. 4(c) for ABC-70 mm^2 and ABC-50 mm^2 conductors, respectively)

Solar PV hosting capacity values obtained from simulations [24], mathematical model (reviewed in Section 2.2) and Nomograms are given in Tables 2,3 for the three types of conductors. The results clearly show that the maximum connectable solar PV capacity levels tend to increase when solar PV units are connected towards the transformer due to minimal voltage rise caused by solar PV units. In this study, hosting capacity relevant to two distinct locations; feeder end and middle of the feeder is evaluated and compared against the mathematical model and the simulations. As shown in the Tables 2,3, solar PV hosting capacities obtained from the simulations and the proposed Nomogram method are in close agreement, confirming the accuracy of the Nomogram.

4. Simplified Solar PV Connection Criteria

The proposed Nomogram based HC assessment approach paves the way for further contributions to improve the solar PV connection guidelines. This approach makes new PV interconnections in a systematic and versatile manner compared with present utility practices based on rules of thumb. From the perspective of rooftop PV deployment in LV distribution networks, it is quite important to have good integration practices upfront, to assure that PV is deployed with the maximum benefit to the community, while maintaining network voltage within stipulated limits. Therefore, the approach proposed in this section provides a straightforward method for new solar PV connections.

4.1. Solar PV Hosting Capacity Limits for LV Distribution Networks

Considering the locational variation of the solar PV systems, two levels of solar PV HC compliant with over-voltage criterion can be identified as the minimum hosting capacity (HC_{min}) and the maximum hosting capacity (HC_{max}), as illustrated in Fig. 5 [7].

With the minimum hosting capacity level, none of the solar penetration levels violate the voltage criterion and solar PV units can be integrated with the network without any concern on the PV location. Between minimum and maximum hosting capacity levels, certain solar PV penetration levels arising from random PV locations may violate the network constraints. Therefore, detailed studies are necessary with precise solar PV locations to verify that a given level of penetration is safe. Moreover, solar penetration levels in excess of the maximum hosting capacity limit, independent of the location of the solar installation will violate the relevant operational limits. These minimum and maximum hosting capacity levels can be further defined based on single distribution feeder or multi-feeder distribution network configurations [7].

Accordingly, for a given feeder, the minimum and maximum hosting capacities can be defined as follows;

- Minimum hosting capacity in a given feeder is the connectable maximum PV capacity at the feeder end and known as the safe limit of hosting capacity (referred to as $HC_{Feeder,Min}$)
- Maximum hosting capacity in a given feeder is the connectable maximum PV capacity at the feeder front (to the transformer) and primarily limited by the thermal over-loading limits of components: eg. feeders and transformer (referred to as $HC_{Feeder,Max}$)

Furthermore, the minimum PV hosting capacity of a given LV distribution network, HC_{min_LV} is the minimum of the safe limits of each feeder and can be formulated as given in (11);

$$HC_{min\_LV} = min\{HC_{F1\_end}, HC_{F2\_end}, \ldots, HC_{Fn\_end}\} \quad (11)$$

where, HC_{Fn_end} is the maximum connectable solar PV capacity at the feeder end of n^{th} feeder ($n = 1, 2, 3, \ldots\ldots$).

Further, maximum PV hosting capacity of a given LV distribution network, HC_{max_LV} is the summation of the hosting capacities at the nearest end to the transformer of each feeder and can be formulated as given in the (12);

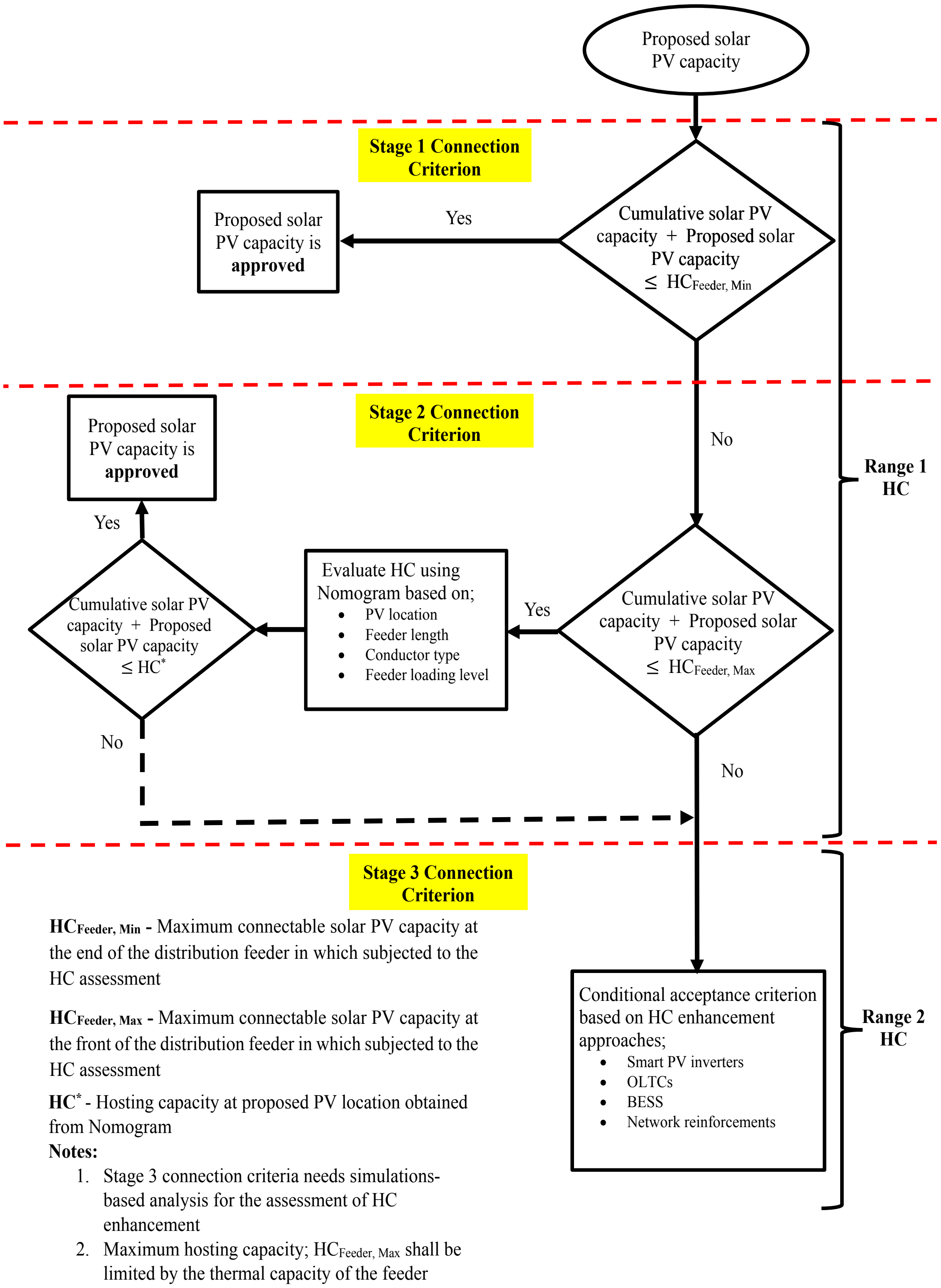
$$HC_{max\_LV} = HC_{F1\_front} + HC_{F2\_front} + \ldots + HC_{Fn\_front} \quad (12)$$

where, HC_{Fn_front} is the maximum connectable solar PV capacity at the feeder front of n^{th} feeder ($n = 1, 2, 3, \ldots\ldots$).

Accordingly, solar PV connection criteria for new solar PV systems are developed in the following section, based on a feeder-level HC definition. The proposed solar PV connection approval criteria can be further extended to an LV distribution network considering the minimum and maximum hosting capacity defined for an LV network.

4.2. Solar PV Connection Criteria at LV Distribution Feeder Level

Proposed solar PV connection criteria comprise three connection stages where the solar PV HC values are evaluated subject to different conditions and classified into two ranges as Range 1 HC and Range 2 HC. Solar PV HC in Range 1 is evaluated under the conditions of; (a) no operational changes in voltage regulation equipment such as OLTCs and capacitor banks, (b) no upgrade of infrastructure/assets such as smart inverters or BESS and (c) no network reinforcements such as replacement of transformers and feeders with larger ones. Note that



HC$_{Feeder, Min}$ - Maximum connectable solar PV capacity at the end of the distribution feeder in which subjected to the HC assessment

HC$_{Feeder, Max}$ - Maximum connectable solar PV capacity at the front of the distribution feeder in which subjected to the HC assessment

HC* - Hosting capacity at proposed PV location obtained from Nomogram

Notes:

1. Stage 3 connection criteria needs simulations-based analysis for the assessment of HC enhancement
2. Maximum hosting capacity; HC$_{Feeder, Max}$ shall be limited by the thermal capacity of the feeder

Fig. 6. Generalised solar PV approval criteria.

maintaining Range 1 solar PV capacity does not incur any additional cost to network operators. However, network reinforcements, infrastructure/asset upgrades and operational changes in voltage regulation equipment can improve the level of solar PV penetration and the corresponding hosting capacity is referred to in this paper as the Range 2 hosting capacity. The extent to which each upgrade could improve the amount of PV that can be accommodated in the grid varies depending on its characteristics. However, reaching Range 2 PV hosting capacity incurs costs for each technological upgrade and depends on the corresponding grid upgrades. Proposed solar PV connection criteria analyse Range 1 hosting capacity in two stages; stage 1 and 2 while in stage 3, Range 2 type hosting capacity is considered.

Fig. 6 shows an illustrative flowchart for the generalised solar PV connection approval criteria, based on the HC assessment using the

Nomogram described in Section 3. Three stages of solar PV connection criteria are summarised in the following subsections;

4.2.1. *Stage 1 Connection Criterion*

In stage 1, safe limit of HC or minimum hosting capacity; $HC_{Feeder,Min}$ is defined as the maximum connectable solar PV capacity at the feeder end. Thus, a new solar PV system can be connected anywhere along the feeder without detailed analysis, until the cumulative solar PV capacity (including proposed PV capacity) is equal to the $HC_{Feeder,Min}$ value. If the total solar PV capacity (cumulative solar capacity $+$ proposed solar PV capacity) exceeds the level of $HC_{Feeder,Min}$, new proposed solar PV connection approvals should be evaluated under stage 2.

Stage 1 connection falls into Range 1 hosting capacity where the new solar PV connection does not require any asset upgrades such as smart inverter and BESS.

With reference to the distribution network discussed in Section 3.2, minimum solar PV HC for $AAC-Fly$ type conductor is 58 kW. New solar PV units can be installed anywhere on the feeder until the cumulative solar PV capacity is equal to 58 kW.

4.2.2. *Stage 2 Connection Criterion*

In stage 2, new solar PV system can be connected to a given feeder subjected to the maximum hosting capacity limit ($HC_{Feeder,Max}$) which is defined as the maximum connectable solar capacity at the front of the feeder. The location of the proposed solar PV system and the feeder characteristics including loading level need to be considered in evaluating stage 2 connection.

If total solar capacity is within $HC_{Feeder,Min}$ and $HC_{Feeder,Max}$, a detailed analysis is required to assess the acceptability of connection of solar PV units based on the Nomogram approach proposed in the Section 3 for the given location. If the total solar PV capacity including the new requested value is below the HC level obtained from Nomogram, the new solar PV connection is approved, otherwise proceed to stage 3. Range 1 type hosting capacity is calculated in this stage as well.

With reference to the distribution network discussed in Section 3.2, maximum solar PV HC for $AAC-Fly$ type conductor is 180 kW which is limited by thermal capacity of the feeder. If the total solar PV capacity is within the range of $HC_{Feeder,Min}$ and $HC_{Feeder,Max}$, solar PV hosting capacity at the proposed location is needed to be evaluated using the Nomogram. If the cumulative solar PV capacity is below than the HC level obtained from the Nomogram, new solar PV unit can be connected at the proposed location.

4.2.3. *Stage 3 Connection Criterion*

If the total solar PV capacity with new proposal is greater than the $HC_{Feeder,Max}$ value for a given feeder, no further solar PV systems can be connected to the network without network upgrades/remedies for over-voltage issue such as network reinforcements (larger conductors and transformers), smart solar PV inverter technology for voltage and power control and integration of BESS. In this stage, enhanced solar PV hosting capacity can be analysed based on simulations with the particular HC enhancement technique proposed to be adopted. Thus, Stage 3 connection criterion can be classified as Range 2 HC.

With reference to the distribution network with $AAC-Fly$ type conductor discussed in Section 3.2, if the total solar PV capacity exceeds the maximum solar PV HC of 180 kW, new solar PV unit shall be connected at the proposed location exclusively only after adopting measures to enhance solar PV HC.

5. Conclusion

A Nomogram based generalised solar PV hosting capacity assessment approach and solar PV connection criteria for LV distribution networks were presented in this paper. The solar PV hosting capacity is essentially constrained in many LV distribution networks by over-voltage limits. Presently, network operators use rules of thumb, which are unlikely to enable the optimum use of existing network assets to maximise the absorption of solar PV generation. Conducting network analysis each time a new application for connection is received, too, is not practically possible, especially for emerging networks and operators, owing to limited resources. Hence, a Nomogram based HC assessment method was developed to conveniently evaluate the maximum allowable solar PV capacity at a given point along a distribution feeder, constrained by over-voltage limits.

The proposed feeder based hosting capacity evaluation through the Nomogram approach can be seen to capture all influential factors on solar PV hosting capacity. Thus, the Nomogram can be used as an approximate guide to evaluate solar PV hosting capacity at a given point of LV feeders without using complex stochastic techniques and deterministic load flow models. Further, distribution network operators and planners can investigate the capability and limitations of solar PV penetration and use the Nomogram as a decision-making tool.

Based on the findings, the minimum level of PV hosting capacity (safe limit of the solar PV hosting capacity) and maximum level of PV hosting capacity have been taken as the baseline for connection criteria for new solar PV connections. The solar PV connection criteria based on the Nomogram tool developed in this paper will be beneficial to electricity distribution utilities who at present, have to deal with voltage uncertainties related to the impact of high penetration levels of PV systems. From a distribution system planning perspective, the use of a generalised selection approach by means of a Nomogram is simple and adoptable in a real-world scenario compared with use of extensive simulations. Furthermore, the proposed systematic approach for HC assessment and PV connection approval contributes to further improvement to guidelines on solar PV installation in LV networks.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Theoretical Background for Basic Determinant of a Nomogram: Proof of (9)

Nomoogram is a diagram representing a formula in which variables are represented by different graduated lines or curves and the solution for a given set of variables can be read by means of an index line. Nomogram has been developed on the basis of the determinants which is a convenient form of representing a mathematical formula [26].

The basic determinant of a Nomogram should satisfy the following conditions if a given formula can be represented in a Nomogram form,

- The absolute value of the determinant must be zero
- Each row must contain one variable only
- The last element of each row must be positive and equal to unity

Nomograms can be classified into various groups and the most convenient way of carrying out this is by classification according to the number of variables contained in the formula, that is called "Class". For example, a formula containing three variables is of the Class-III Nomogram. Class of the Nomogram is equivalent to the number of different curves or lines to be constructed in the Nomogram. However, Class of a Nomogram has no connection with the degree of variables in the formula.

For a given formula in Class III, which contains variables u, v and w, the basic determinant of the Nomogram is formed as given in (Appendix A.1).

$$\begin{vmatrix} g_1(u) & f_1(u) & 1 \\ g_2(v) & f_2(v) & 1 \\ g_3(w) & f_3(w) & 1 \end{vmatrix} = 0 \qquad \text{(Appendix A.1)}$$

where $(g_1(u), f_1(u))$, $(g_2(v), f_2(v))$ and $(g_3(w), f_3(w))$ represent the curves of the variable u, v and w in x, y Cartesian plane, respectively. Nomogram can be constructed by plotting the positions of the points $(g_1(u) = x_1, f_1(u) = y_1)$, $(g_2(v) = x_2, f_2(v) = y_2)$ and $(g_3(w) = x_3, f_3(w) = y_3)$ which represent the curves of u, v and w in the Cartesian plane.

In general, if three common points in each locus satisfy (Appendix A.1), those three points are co-linear. This implies that respective values of the variables u, v and w satisfy the given formula. In the view point of the co-ordinate geometry, each line or curve in a Nomogram may be regarded as a set of points representing successive values of one of the variables in the formula which the Nomogram as a whole presents.

However, any formula that met with in practice shall be rearrange to form of basic determinant before the corresponding Nomogram can be designed and constructed. An example has been worked out below. Consider the formula,

$$u^2 + uv = w \qquad \text{(Appendix A.2)}$$

Re-writing (Appendix A.2)

$$u^2 + uv - w = 0 \qquad \text{(Appendix A.3)}$$

Take $x = v$ and $y = w$ and substituting to (Appendix A.3), the following set of equations can be obtained;

$x - v = 0$

$y - w = 0$

$u^2 + ux - y = 0$

Since, all three equations are true, the following determinant is zero.

$$\begin{vmatrix} 1 & 0 & -v \\ 0 & 1 & -w \\ u & -1 & u^2 \end{vmatrix} = 0 \qquad \text{(Appendix A.4)}$$

(Appendix A.4) can be transformed into the form of (Appendix A.1) by applying row and column operations appropriately.

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