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RESEARCH ARTICLE

Estimation of Photovoltaic Hosting Capacity Due to the Presence of Diverse Harmonics in an Active Distribution Network

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ABSTRACT Renewable distributed energy resources are the solution to rising power demand, but their integration is a difficult technological undertaking that requires careful planning. Distributed energy resources are mostly incorporated in the final level of power system networks, where harmonic content swings are highest. At the planning stage, the highest potential power injection, i.e., hosting capacity, is estimated while taking into account the main anticipated operational challenges, one of which is undesirable harmonics. But it is not possible to include all operational harmonic orders precisely for accurate hosting capacity estimation. The presence of harmonics affects the hosting capacity of the network to a considerable extent. In this work, operational derated hosting capacity is proposed to enhance the situational awareness for calculating the change in hosting capacity of the network due to the presence of operational dominant harmonics, as compared to the ideal condition. Additionally, the effect of harmonics on the power factor of the network nodes are also investigated thoroughly, abiding the limits of IEEE-519-2014. Because in any distribution network, unbalance cannot be neglected, operational derated hosting capacity is also extended for testing unbalanced conditions within the network. Indicators such as voltage, current, harmonic distortion, and power factor are studied thoroughly to analyze the derated hosting capacity. To justify the effectiveness of the proposed work operational derated hosting capacity is compared with the existing literature. A reconfigured IEEE-33 bus distribution network is considered for assessment. The authors utilized MATLAB along with Typhoon HIL real-time platform for modeling as well as for validation of the results.

INDEX TERMS Active distribution network (ADN), hosting capacity (HC), operational derated hosting capacity (ODHC), photovoltaic distributed generation (PVDG), situational awareness (SA), driving point impedance (DPI), driving point reactance (DPR), total harmonic distortion (THD).

NOMENCLATURE

Variables

V_{PCC}	Voltage at PCC.
V	Utility voltage.
V^h	Voltage considering harmonics.
P^h_{ODHC}	Operational derated hosting capacity in presence of harmonics.
S	Apparent Power.
$P_{planned}$	Calculated HC in the absence of harmonics.
P_{Load}	Load Power.
Z_{th}	Effective Thevenin's impedance.
n	Number of buses of the distribution network.
P_{pv}	Active power generated by PV.
Q_{pv}	Reactive power support by PV.
Q_{Load}	Reactive power demand at a bus.
R_{ij}, X_{ij}	Resistance and reactance between 'i^{th}' and 'j^{th}'bus.
Z_h	Impedance in the presence of harmonics.

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Z_{ij}	Impedance between 'i^{th}' and 'j^{th}'bus,.
${p_{ij}}^h$	Harmonic contribution factor for 'h^{th}' harmonic between 'i^{th}' and 'j^{th}'bus.
h	Variation of electrical parameters in the presence of harmonics.
THD_i	Total harmonic distortion at bus i.
Y_{bus}, Z_{bus}	Bus admittance and impedance matrix.
I_{bus}, V_{bus}	Bus current and voltage injection matrix.
$P^h_{V\_X}$	Estimated power injection considering Harmonics affecting voltage and line reactance.

Abbreviations

HC	Hosting capacity.
DPI	Driving point impedance.
DPR	Driving point reactance.
ADN	Active distribution network.
DER	Distributed energy resources.
WECS	Wind energy conversion systems.
PVDG	Photovoltaic distributed generator.
THD	Total harmonic distortion.
ODHC	Operational derated HC.
pf	Power factor.
GA	Genetic algorithm.
DHPF	Decoupled harmonic power flow.
PSO	Particle swarm optimization.
SA	Situational awareness.
FFT	Fast Fourier Transform.

I. INTRODUCTION

With the growing population and greater requirement for power, there has been a significant increase in the usage of renewable sources in the distribution system. These renewable-based distributed energy resources (DERs) mainly include wind energy conversion systems (WECS), and photovoltaic distributed generators (PVDGs). DERs help the consumers generate their own power, lessening the substation's burden. It has several other benefits, which include reliability improvement as compared to the traditional method [1], environmental benefits, line loss reduction, and voltage profile improvement [2], [3], [4]. The most popular DER being used in the distribution system is the PVDG due to its easy installation, government subsidies, and economic benefit to consumers [5]. Due to these causes, consumers in the utility are sympathetic towards the integration of more and more PVDG from their end, which may cause various issues with power system operational and power quality parameters [6].

Maximizing the DER integration into the distribution system is an important aspect of providing reliable power to the consumers. While power injection is carried out using DERs, the variations in operational parameters for the power system network should also be considered [7], [8], [9]. The maximum permissible amount of power injection into the network without violating the power system limits such as voltage, current, and total harmonic distortion (THD) is termed as hosting capacity (HC) of the network [10]. The network HC is affected due to various parameters, including permissible voltage limits by the utility, conductor ampacity limit, non-sinusoidal source voltages and currents caused by nonlinear loads [11]. Rapid advancements in power electronics technology, ensure its wide application across a broad spectrum of sources and loads, contributing to more nonlinear currents in the distribution system. The effect of these nonlinear currents on the power system is one of the major operational concerns. It is also evident from [11] that the current distortion caused at the load side and voltage distortion of the utility side, adversely affects the network's HC. Considering the established fact that load side distortion degrades the performance of active distribution networks (ADN) more frequently, researchers addressed this issue in various possible manner. In [12], the authors presented an optimization-based study for HC analysis in the presence of harmonics in ADN. Decoupled power flow is utilized to find non-fundamental components of voltage and currents. To mitigate the harmonic content, a single tuned filter in the ADN is proposed in [12], which improved the HC. In [13], the authors proposed a C-type filter to improve the power factor (pf) and HC of ADN. The authors compared this filter with the traditional one and found it to be superior in improving HC, voltage regulation, and pf. Considering the technical advantage of low power loss at fundamental frequency and no resonance problem, the authors in [14] proposed genetic algorithm-based C-type filter design. Simultaneously, the maximum DER penetration limit is also optimized along with filter sizing in [14]. This solution to the optimization problem is found using the grid search method. Pareto-based multi-objective firefly algorithm is adopted in [15] to design a third-order damped filter to minimize the non-fundamental components of current. Along with parameter selection for filter design, DG size is also optimized to minimize the adverse effects of harmonics. Further, the cost of the filter is also optimized making it suitable for working in the distribution grid, under a non-sinusoidal environment. The mitigation of harmonics is also performed in the planning stage, where the application of passive filters is emphasized. The authors in [16] adopted an adaptive bacterial foraging optimization for placement and size selection of passive power filters to enhance the HC of the distribution system. To mitigate the harmonics in the distribution system, the authors in [17] presented a detailed analysis of various active, passive, and hybrid filters applicable for ADN to improve the HC. This work also emphasized on integration of harmonic mitigation devices at the inverter end. Even though, the integration of additional devices showed a noticeable improvement in harmonic mitigation as in [12], [13], [14], [15], [16], and [17]; but, some additional strategies based on network reconfiguration are also adopted to mitigate the harmonics, and mathematical modeling are performed to solve the HC problem in the presence of harmonics, in [18], [19], and [20]. Authors in [18] proposed a two-stage solution for reconfiguration using non-dominated sorting genetic algorithm II and fuzzy decision-making for minimizing harmonics and improvement of voltage profile in the distribution system. To reconfigure the network the authors used multiple circuit breakers in the distribution network. In addition to the optimal reconfigured network, the authors in [19] also presented real-time results for THD as an indicator with the reconfiguration of distribution network. The authors in [20] however adopted mathematical modelling to study the nonlinearity effects due to harmonics on HC in case of non-convex problem.

From the extensive literature review, it can be inferred that nonlinearity of any kind adversely affects the HC of the ADN by affecting the voltage, current and line parameters. In the distribution network, it is an established fact that the harmonic due to non-linear load is more frequent as compared to source distortion. Considering this fact, some of the researchers addressed this problem by integrating harmonic mitigation devices or proposed some strategy that reduces the harmonic content and increases ADN's HC. But use of additional filters adds to the principal investment of utility. The degree of harmonic mitigation depends on the filter size; hence, the capital investment proportionally increases to achieve higher harmonic filtration. The single-tuned filter may cause issues when the connected load capacity changes. For some specific types of filters, resonance problems also may occur. Further, placement of filters requires added maintenance to sustain the network reliability. Network reconfiguration seems to be a good alternative for harmonic reduction, but it also has some limitations. Reconfiguration requires trained workforce, the decision of optimal reconfiguration according to variation in load requires appropriate estimation, also incorporation of additional breakers lead to an increase in overall cost. With this dynamic reconfiguration, the impedance at each point of common coupling (PCC) changes, leading to degraded filters' performance. From the available literature it is established that researchers addressed the harmonics issue with an aim to minimize it with additional equipment or methods that indirectly involve some of the extra equipment. Perceiving all the shortcomings related to PVDG integration into an ADN, and the quest to estimate the more exact power injection, an additional device-independent system, computationally efficient method with low resource requirement, and reliable approach for power injection estimation is required. In this regard, this research aims to estimate HC considering harmonics as a contributing factor leading to operational derated HC (ODHC) assessment unlike the available literatures where harmonics is presented majorly as an indicator.

The organization of the rest of the manuscript is as follows: Section II highlights the research objectives. Section III presents the effect of harmonics on photovoltaic HC estimation. Section IV details the proposed ODHC estimation in the presence of diverse harmonic order environment. Section V analyzes the results, and Section VI showcases the comparison of the proposed method with the existing literature. Finally, section VII concludes the findings.

II. OBJECTIVES

From the literature survey, it is observed that the existence of harmonics is unavoidable in ADN. Identifying harmonics as an indicator and utilizing additional devices for it's mitigation is not favorable in all conditions, as a wide range of constraints such as cost, optimal placement/ size etc. are involved. At the same instant, power injection using DERs is crucial in the present grid scenario for reliable power supply. In practical ADN, THD affects power injection, due to variation in voltage, and change in impedances. Considering the overall practical picture of ADN, to showcase the effect on the power injection a set of objectives are summarized as follows:

i. Analyzing the effects of THD on line impedances with change in harmonic content of line current according to IEEE standard.
ii. Investigation of variation of pf of nodes in ADN due to the change in the harmonics.
iii. Re-estimation of derated HC over planned HC based on (i) & (ii), and validation of results for ODHC both for balanced and unbalanced ADN according to IEEE standards.
iv. Verification of results in hardware-in-loop (HIL) based real-time environment, to prove the efficacy of incorporating the proposed ODHC estimation in ADN.

III. EFFECT OF HARMONICS ON PHOTOVOLTAIC HOSTING CAPACITY ESTIMATION

Nonlinear loads, and power electronic devices draw currents that are of a frequency other than the fundamental frequency. With the surge of nonlinear load usage by the consumers in the distribution network, there has been a spike in the harmonic injection in the distribution network. This makes the distribution network rich in harmonics, which leads to distortion in current and voltages in the system. These harmonics need to be under certain limits, as defined by IEEE 519 standard [21], [22]. The distortions caused by these harmonics on the current and voltage waveform may even lead to the violation of predefined operational limits of HC in the distribution system [23]. It may also change the line parameters of the distribution network, thereby causing a change in the overall power flow of the system [24], [25]. So, there is a need to study the changing network parameters, such as effective line impedance, driving point impedance (DPI), and pf and its effect on the HC estimation.

Figure 1 shows an equivalent circuit for a part of distribution network with PVDG integrated at PCC along with load. The effective Thevenin's impedance at PCC is represented by Z_{th}. Considering this, the real power that can be injected at PCC can be calculated using the following expression as presented in equation (1) [19].

$$[P_{planned}]_{(n-1)\times 1} = \left\{ [V_{pcc}]_{(n-1)\times 1} \times \frac{\left\{ [V_{pcc}]_{(n-1)\times 1} - [V]_{(n-1)\times 1} \right\}}{\left\{ [R_{Th}]_{(n-1)\times 1} + \left([X_{Th}]_{(n-1)\times 1} \, [tan\varphi]_{(n-1)\times 1} \right) \right\}} \right\} + [P_{load}]_{(n-1)\times 1} \tag{1}$$

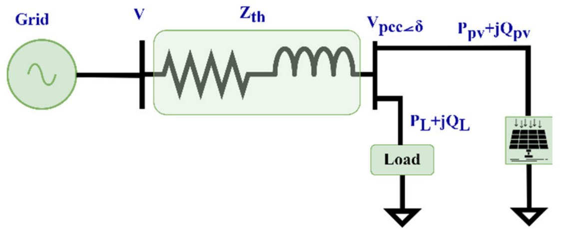

FIGURE 1. Equivalent circuit of a part of distribution network for HC calculation with integrated PVDG and load.

Equation (1) represents the active power injection, when there is no nonlinearity present in the ADN. It can be observed from the equation that harmonics effects are not considered in the effective Thevenin impedance and in the power factor.

The net available power, when PVDG is connected at PCC according to equation (1) can be expressed as in equation (2):

$$S < \varphi = \left(P_{pv} - P_{Load}\right) + j\left(Q_{pv} - Q_{Load}\right) \tag{2}$$

In the presence of harmonics, the real power injection i.e, $P_{planned}$ in equation (1), degrades as presented in equation (8). A direct load flow (DLF) is adopted from [19] to evaluate and analyze all the necessary voltages and currents in the network due to power injection as per equation (1).

The HC of an ADN may be limited due to harmonic current impact, and hence the contribution of net available power at PCC due to DER may reduce [11]. Harmonics may not only diminish the HC of the network, but may also affect various other parameters such as node voltage, pf, and DPI as reflected in figure 2. Due to the nonlinear load, current harmonics can be injected into the system. These current harmonics gradually can cause voltage distortion in the network. It is to be noted that when the current flowing through the line contains harmonics, other than fundamental components, the reactive component of the line parameter may also get affected. All these variations in the power system parameters due to harmonics can affect the overall HC of the network, hence change the overall power flow in the network.

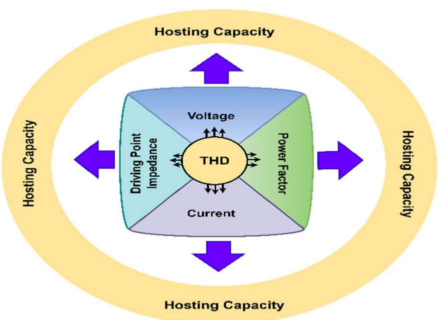

FIGURE 2. Effect of THD on power system parameters for HC assessment.

A. ASSESSMENT OF EFFECTIVE LINE IMPEDANCE DUE TO DIVERSE HARMONIC RICH ACTIVE DISTRIBUTION NETWORK

Harmonic analysis needs to be performed on a considered system to understand the effect of different harmonic orders affecting the power flow. Considered network needs to be analysed for various dominant frequencies collectively, as any distribution system is subjected to current injections with multiple harmonic frequencies. The effective line reactance in the presence of harmonics can be calculated by calculating the contribution of the individual harmonic component in the total line current. Fast Fourier transform (FFT) analysis is used as a tool for calculating the contributions of the individual harmonic order. The resultant of all the dominant harmonic order can be calculated by equation (3) [26].

$$\left[Z_{ij}\right] = R_{ij} + j\sum_{h=1}^{(2h-1)} {p_{ij}}^{h}.X_{ij} \tag{3}$$

It can be observed from equation (3) that with increase in contribution of different harmonic order in line current, the reactive component in the line parameter increases. Hence with increase in harmonic components the resultant harmonics sum-up to impact the DPI.

B. ASSESSMENT OF EFFECT OF DRIVING POINT IMPEDANCE IN THE PRESENCE OF HARMONICS

The HC at a node is dependent on various parameters such as voltage limit, effective line impedance, and pf which is showcased in figure 2. Out of these parameters, DPI is one of the major parameters. With increase in DPI due to the increased contribution of different harmonic orders, the effective HC may decrease. The DPI at a node is contributed by the effective line impedances of ADN, which is defined as the equivalent impedance considering a specific bus as reference as depicted by each elements in equation (5).

In the distribution network to calculate the DPI, Z_{bus} needs to be calculated. The evaluation of Z_{bus} matrix can be done by utilising the Z_{bus} building algorithm [27], [28], [29]. This method requires stepwise addition of every single element until all the buses and components are added into the network. For a $'n'$ bus distribution network, the size of the Z_{bus} matrix is given by $(n-1)\times(n-1)$ keeping one of the buses as reference bus (Bus 0). The voltage at any bus can be represented by equation (4) considering 'Z_{bus}':

$$V_{bus} = Z_{bus}I_{bus} \tag{4}$$

For an n-bus system, the Z_{bus} can be written as in equation (5), where the diagonals elements of bus impedance matrix i.e., Z_{11}, Z_{22} and $Z_{(n-1)\times(n-1)}$ are the DPIs at bus 1, bus 2 and bus (n-1), respectively with bus 0 as the reference bus.

$$[Z_{bus}]_{((n-1)\times(n-1))} = \begin{bmatrix} z_{11} & \cdots & z_{1\times(n-1)} \\ \vdots & \ddots & \vdots \\ z_{(n-1)\times 1} & \cdots & z_{(n-1)\times(n-1)} \end{bmatrix}_{((n-1)\times(n-1))} \tag{5}$$

These diagonal impedances are also the Thevenin's impedances at respective buses on which the power injection depends as shown in equation (1). The non-diagonal impedances represent the transfer impedance of the buses. The Z_{bus} building algorithm is an efficient way to calculate the DPI than the conventional method of calculating DPI using bus admittance matrix (Y_{bus}). The Z_{bus} building algorithm eliminates the complexity of calculating the inverse of Y_{bus} for a larger bus distribution network. The input parameters for the Z_{bus} requires the bus data which are readily available for distribution networks. Hence this algorithm proves to be efficient in calculating the DPI in the presence of harmonics in distribution networks.

With the increase in harmonic content in the distribution network, the effective line impedance increases as per equation (3). The updated impedance values from equation (3) are utilised to calculate DPI and form 'Z_{bus}' matrix as in equation (5). The increased DPI due to high harmonic content may decrease in the HC of the node as detailed in equation (6). The pictorial representation of the same can be observed in figure 3, where it can be observed that with increase in the THD of line current, the HC decreases. The minimum value of HC is attained at the limiting value of THD i.e., line *BC* as in figure 4. The area "*BCEF*" represents the minimum value of HC which represents the maximum derating of HC, whereas point 'D' signifies maximum HC, which corresponds to ideal case, validating equation (1).

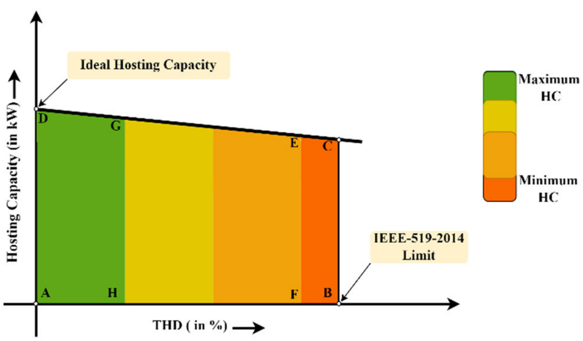

FIGURE 3. Variation of HC with change in THD.

The HC varies as the parameters explained in section III-A and III-B such as voltage, and impedance varies due the variation in THD, which can be observed from equation (6).

$$\left[P^h_{V\_X}\right]_{(n-1)\times 1} = \left\{\left[V^h_{pcc}\right]_{(n-1)\times 1} \times \frac{\left\{\left[V^h_{pcc}\right]_{(n-1)\times 1} - \left[V^h\right]_{(n-1)\times 1}\right\}}{\left\{[R_{Th}]_{(n-1)\times 1} + \left(\left[X^h_{Th}\right]_{(n-1)\times 1}[tan\varphi]_{(n-1)\times 1}\right)\right\}}\right\} + [P_{load}]_{(n-1)\times 1} \tag{6}$$

It can be observed from equation (6) that with increase in the harmonics content due to load current, the HC decreases at the specific node. This is due to the incremental change in the value of X_{Th} to X^h_{Th}. The increment in the value of reactance can cause voltage drop, which further diminishes the HC. Due to this phenomenon, the PVDG injection reduces at a specific node '*n*' as compared to that of equation (1). Additionally, pf also varies due to variation in harmonic components of voltage and current. The effective pf is the actual pf that is responsible for active power consumption at the PCC. The effect of harmonics on pf is elaborated in subsection III-C.

C. ASSESSMENT OF EFFECT ON POWER FACTOR IN THE PRESENCE OF HARMONICS

The presence of harmonics distorts the voltage and current waveforms which leads to changes in the delivered power. Current being the most distorted signal in this scenario, causes the pf to change. The new pf is expressed as a function of the nominal pf and current THD [30], [31]. This can be expressed by the equation (7).

$$\left[(pf_{New})_i\right]_{(n-1)\times 1} = \left[cos\varphi^h\right]_{(n-1)\times 1} = \frac{[pf_i]_{(n-1)\times 1}}{\sqrt{1+\left\{[THD_i]_{(n-1)\times 1}\right\}^2}} \tag{7}$$

Equation (7), showcases the apparent pf due to distorted current for a '*n*' bus distribution system. With increase of THD in line current, the pf decreases as in equation (7), which causes the apparent power to increase proportionately, but the effective real power corresponding to the fundamental frequency remains unchanged. All these phenomena contribute to a remarkable change in pf and hence the HC. The collective effect of pf at all nodes on HC in highly harmonically polluted ADN may diminish the overall HC. Taking the derating into consideration, injection should be selected carefully, so that no adverse condition arises due to it. This derating in injection can be represented as in equation (8), considering all affected system parameters by the harmonic.

$$\left[P^h_{ODHC}\right]_{(n-1)\times 1} = \left\{\left[V^h_{pcc}\right]_{(n-1)\times 1} \times \frac{\left\{\left[V^h_{pcc}\right]_{(n-1)\times 1} - \left[V^h\right]_{(n-1)\times 1}\right\}}{\left\{[R_{Th}]_{(n-1)\times 1} + \left(\left[X^h_{Th}\right]_{(n-1)\times 1}\left[tan\varphi^h\right]_{(n-1)\times 1}\right)\right\}}\right\} + [P_{load}]_{(n-1)\times 1} \tag{8}$$

Considering the facts showcased in section III, it can be deduced that line impedance, DPI, and pf may degrade due to the presence of harmonics in ADN. Hence, a novel methodology is adopted in section IV to precisely calculate the HC and to avoid any adverse operational issues due to harmonics.

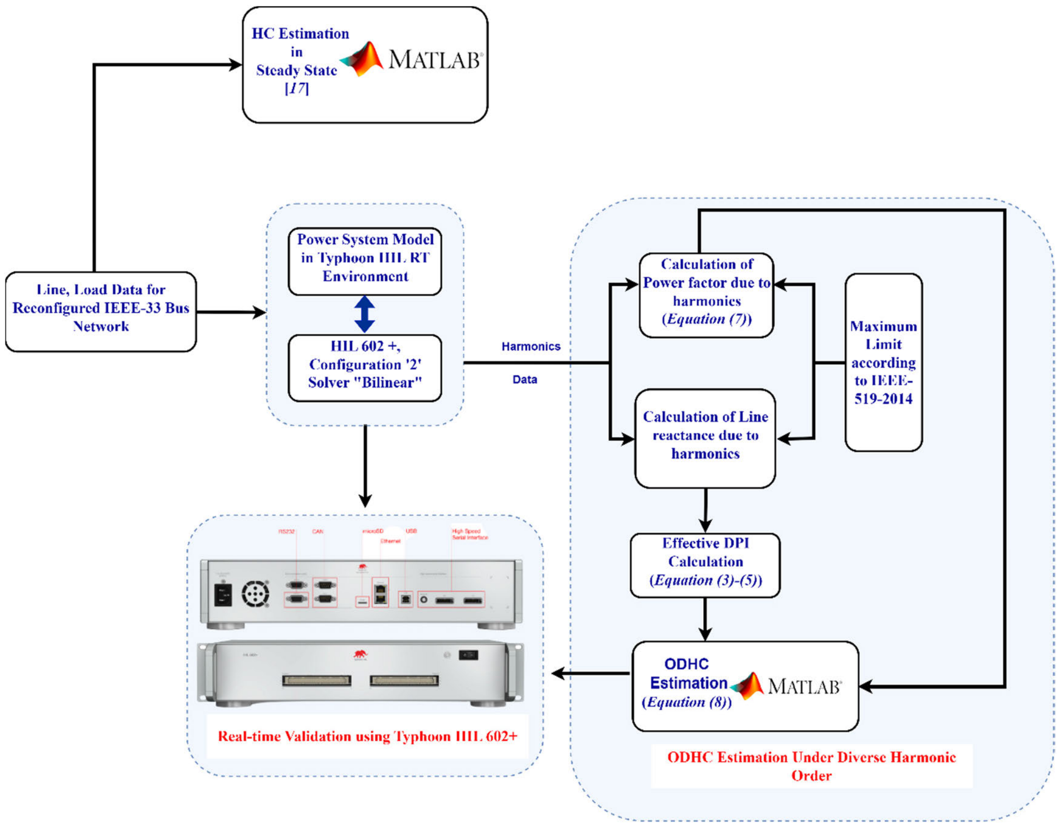

FIGURE 4. **Proposed methodology for operational derated hosting capacity estimation under diverse harmonic order.**

IV. PROPOSED OPERATIONAL DERATED HOSTING CAPACITY ESTIMATION UNDER DIVERSE HARMONIC ORDER ENVIRONMENT

Although HC is calculated at the planning stage, considering various possible harmonics that could be injected into the system by the non-linear loads. But when the SPVs are in operation along with the loads, there could be different order of harmonics which are considered at the planning stage. However, it is impossible to estimate the overall effect of all non-linearities due to connected loads collectively on any particular equipment, node or on any power system parameter. This is one of the practical and most common issues in the distribution system, when the passive distribution system shifts its status to active aggressively. In this proposed ODHC strategy as shown in figure 5, this problem is addressed, with minute details and real-time verification that further fortifies the claim. To achieve the objective, HC is calculated for the ideal system where THD is not present, using DLF method in MATLAB scripting [19].

Considering the line and load data, a schematic model is developed in Typhoon HIL real-time environment compatible with Typhoon HIL 602+ real-time simulator. For this real-time high-fidelity model, the harmonic contents are measured, as it resembles the actual SPV system. To observe the effect of harmonics for practical case, in this work high fidelity real-time models of loads are considered. These models inject harmonics which are identical as that of the practical loads, hence accurate effective line reactances can be calculated, as the line resistance value is immune to the frequency changes. Harmonics injection caused by non-linear loads and SPV not only influence the reactance values, but, the pf values also varies, which is calculated using equation (7). These two values later are utilized to ODHC estimation of the network as per equation (8), as this work aims to estimate the maximum possible degradation in HC due to harmonics. Considering the above discussion, it can be inferred that HC capacity is affected by the variation of pf and line parameters, which is caused by harmonics content in the power system network. This can be summarized as in equation (9).

$$P_{ODHC} \propto {}^{1}\!/_{Z_h};\ 0 < h \leq h_{Max,IEEE-519} \tag{9}$$

Maximum possible harmonics in the line, nodes, and at DG integrated nodes are considered according to IEEE-519-2014 Std. The extreme values of harmonics which signify maximum allowable THD according to IEEE-519 standard is utilised to calculate the maximum possible operational degradation in HC in the presence of non-fundamental frequencies. At last, the ODHC is verified using voltage as an indicator in Typhoon HIL 602+ real-time environment [32]. The details regarding different considered scenarios along with results according to proposed methodology is presented in the section V along with the details of hardware setup.

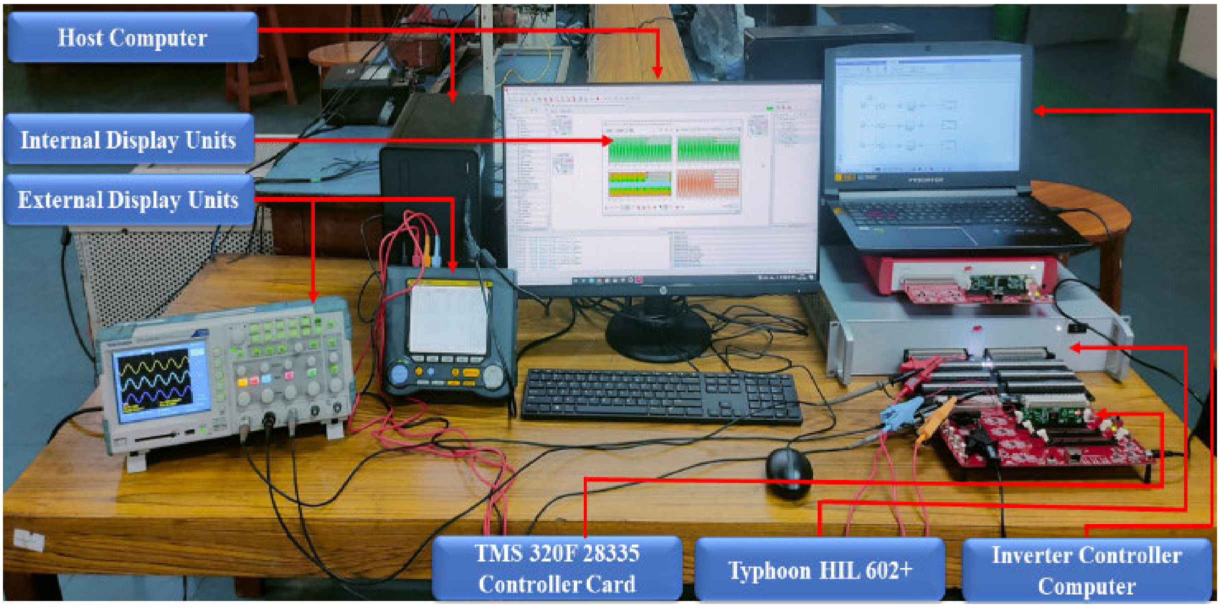

FIGURE 5. Laboratory setup for estimation of operational derated hosting capacity due to diverse harmonics order in active distribution network.

V. RESULTS AND ANALYSIS

To showcase the efficacy of the proposed strategy, a reconfigured IEEE -33 bus network is considered [19]. This network is considered due to the limitation of the real-time simulation hardware, but this process is applicable for all distribution networks. In this work, the solar photovoltaic (SPV) are connected at the end nodes of the distribution system, namely at the nodes 2,7,10,14,25,32, and 33, with capacity 252.9053 kW, 205.327 kW,62.435 kW, 121.728 kW, 424.63 kW, 212.039 kW and 61.147 kW respectively for ideal case. For analysis, both MATLAB and Typhoon HIL real-time digital simulator are used. A 6-core FPGA-based Typhoon HIL 602+ real-time digital simulator is used, which is connected to a core i7 computer with 16 GB RAM via USB 2.0 type 'B' connector, as shown in the experimental setup as in figure 5. For all the real-time measurements, internal high-fidelity scope and measurement widgets are used. In this work, firstly three cases are considered to showcase the claimed HC calculation for balanced network, which are:

a. Ideal case: no harmonic present in ADN
b. Practical case: nominal harmonic present in ADN
c. Extreme case: maximum permissible THD according to IEEE 519-2014 standard; considered to estimate the degradation in HC.

The ideal case refers to a condition where there is no harmonics present in the system. Although this condition is very difficult to achieve, but to analyse practical cases, ideal case needs to be thoroughly evaluated as a reference. MATLAB scripting is utilised in this case to analyse the power injection and its performances. To analyse the practical case, nominal harmonics which are inherently present in the system are considered. For this case real-time modelling is used and results are recorded in the high-fidelity meters and scopes. To analyse the extreme cases, i.e., ADN with maximum permissible THD according to IEEE-519-2014, equation (3)-(8) are utilised along with the DLF method to calculate the effect of maximum permissible THD on HC estimation.

The calculated injection for the extreme case is also validated in the real-time simulation platform. To add a step further, an unbalanced ADN is also considered to obtain a clear picture of the effect on HC due to the presence of diverse harmonics. Both MATLAB scripting as well as real-time models are developed even for the unbalanced case to analyze the results.

For ideal case as in (a) upon performing harmonic analysis, it is observed that there are no harmonic content present also reflected through figure 6. For the practical case as in (b), it can be observed again from figure 6 that different values of THD are present in the lines of the distribution system. These line THD data collected from real-time simulation, although adhere to the IEEE-519-2014 Std., but contributes to some parametric change in the imaginary part of the line impedance. This parasitic change due to harmonics on the distribution line reactance, causes degradation in power injection as reflected in equation (8). It is worth noting that unlike case (b), for ideal case, as in case (a); the HC is also more, as reflected in equation (1) due to absence of additional impedance-imposed harmonics.

Figure 7 shows the maximum limit of THD that is acceptable in the distribution system according to the ratio of short circuit current (I_{SC}) to the load current (I_L) which is stated in standard IEEE-519-2014. It can be noted from figure 7 that for node 2, 7, 10, 14, 25, 32, and 33, the above-mentioned ratio differs, as these nodes are connected with SPVs. According to IEEE-519-2014, it can also be deduced that the nodes where SPV or any DERs are

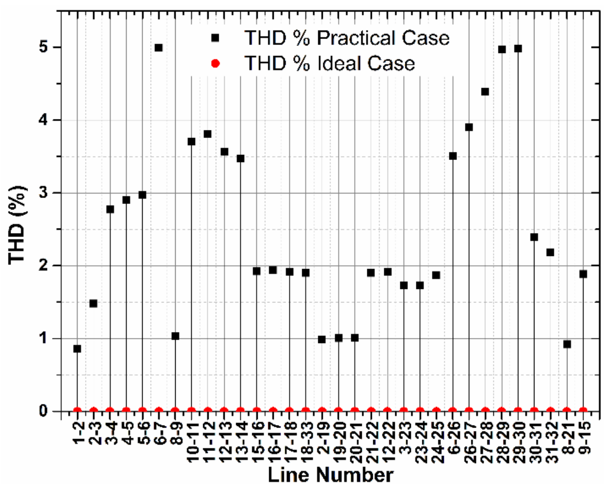

FIGURE 6. Real-time line current THD values for reconfigured IEEE-33 bus active distribution network.

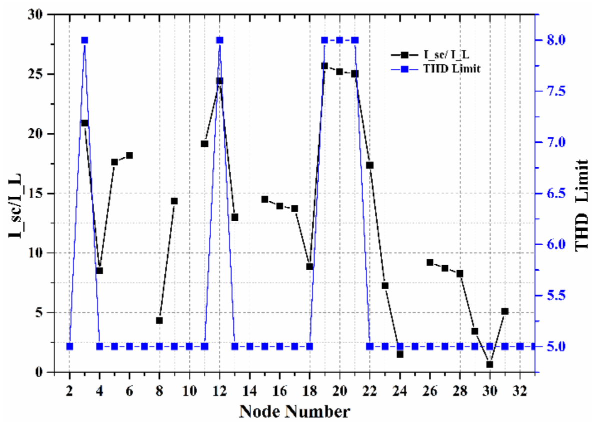

FIGURE 7. Node wise THD limits according to IEEE-519-2014 for IEEE 33 bus reconfigured active distribution network.

TABLE 1. Variation of harmonics with voltage rating of power system network.

PCC Voltage	Individual Harmonics %	THD (%)	Maximum harmonics observed
V<= 1kV	5	8	NA
1 kV< V<=69 kV	3	5	4.9(L6-L7,L28-L29,L29-L30)

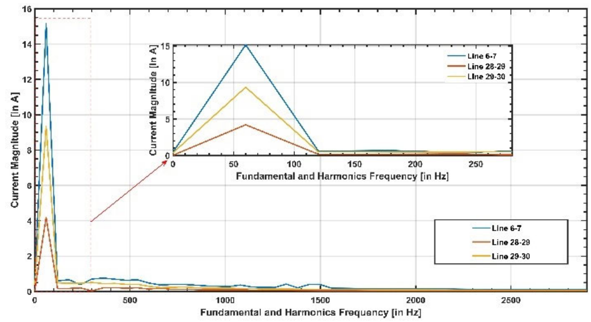

FIGURE 8. Contribution of each harmonic order frequency on Current magnitude for practical case.

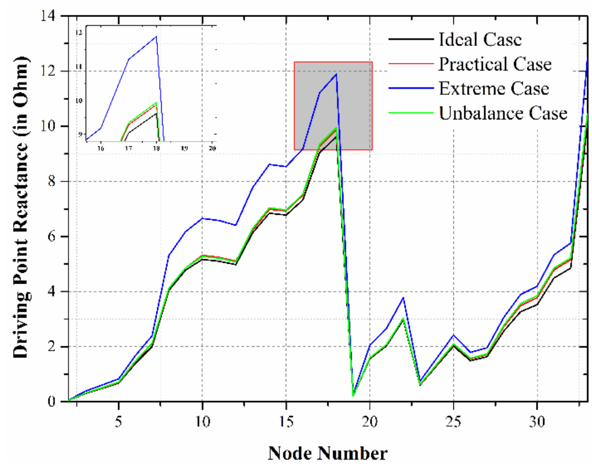

FIGURE 9. Driving point reactance values for reconfigured IEEE-33 bus active distribution system.

connected, the maximum THD limit can be 5% irrespective of the ratio "I_{sc}/I_L".

This can also be confirmed from table 1, where the maximum allowed THD for rated voltage of 12.66 kV is 5%. For voltages below 1kV the allowable THD is 8% and maximum allowable individual harmonic content is 5%.

According to IEEE-519, it is essential to ensure the permissible level of individual harmonics order. Figure 8 shows the contribution of each harmonic order till 50th order. It can be observed that the individual contribution of each order is also less than 5 % for practical case. The harmonic order graph is shown for three lines as per table 1, where maximum harmonics is observed.

Different levels of harmonic order leads to the change in line reactance which contributes to the change in DPI as presented in equation (5). This phenomenon is observed in figure 9. It is worth noting from figure 9 that with increase in line current harmonics, the DPI of each node of the network increases, as the line reactance increases. Since the harmonic content affects only the line reactance, the DPI can be more appropriately presented in the form of driving point reactance (DPR).

Hence, the changes in the value of DPR due to presence of THD for various cases such as practical, extreme, and unbalanced with respect to ideal case can be observed in figure 9. In figure 9 it can be observed that for the practical case, the DPR value lies above the ideal value, as in practical case impact of harmonic content is higher as compared to the ideal case. Analysis for extreme case is also presented in figure 9, where maximum allowable THD is considered according to IEEE-519-2014 standard. It can be derived that for extreme case the variation in maximum. In the event of unbalance in the network, uneven harmonic current flows in the distribution network which also contributes to change in DPR by changing the line reactance. It can be seen from figure 9 that the unbalanced case has greater variation in reactance value over the ideal value and practical case, but less than the extreme case.

Figure 10 depicts the percentage rise in DPR as compared to the ideal condition. It is evident from the result presented in figure 10 that, with increase in harmonic content in the distribution system, the DPR increases at almost all of the nodes, with a few exceptions. Figure 10 enables the utility to identify these exceptional nodes which can be used to connect the devices that are very sensitive towards the variation in harmonics.

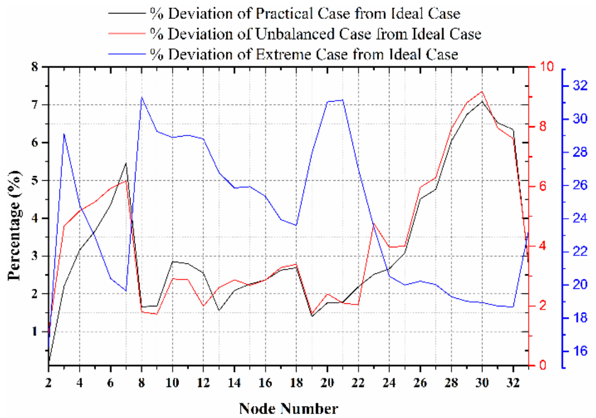

FIGURE 10. Percentage variation in driving point reactance at different nodes for reconfigured IEEE-33 bus active distribution network.

Further, not only does the DPI change due to the THD in the network, the pf also varies due to the THD in the network. Although the variations are nominal, it's collective effect on the HC is compelling. Real-time results from figure 11 reflect an increasing adverse effect of harmonics on pf due to an increase in harmonic content. Considering the adverse effects due to the harmonics, online reactance, DPI, and pf, the ODHC is estimated and showcased in figure 12 and 13 respectively. In figure 12, it can be witnessed that the planned HC as per the ideal case varies with change in the harmonics content in the system. It is worth noting that the cumulative derating in HC across the seven nodes is about 14 kW for extreme case, whereas for practical case the cumulative derating is about 7.7 kW as compared to the ideal case.

It can also be observed from the results as in figure 9, 10 and 12, that although with increasing harmonic content, the overall HC derating increases, but the derating in HC is not proportionately distributed. This observation is vital for the distribution system operator (DSO) to identify the sensitive nodes subjected to maximum derating due to harmonic content and restrict inadequate integration. Along with the presented nodes as in figure 12, other nodes in the reconfigured IEEE-33 bus ADN are also subjected to diminished HC, which is cumulatively about 25 kW considering all nodes for extreme case, and 9 kW for practical case as shown in figure 13.

In addition to the derating in HC of the ADN, the variable losses are also found to increase for the extreme case as compared to the practical case due to the inclusion of more harmonic as reflected in figure 14. The power losses due to

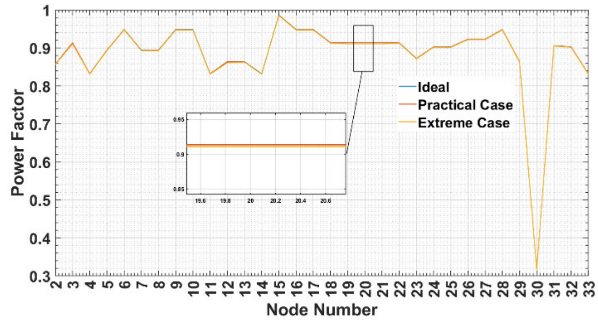

FIGURE 11. Real-time power factor values at different nodes of reconfigured IEEE-33 bus active distribution system.

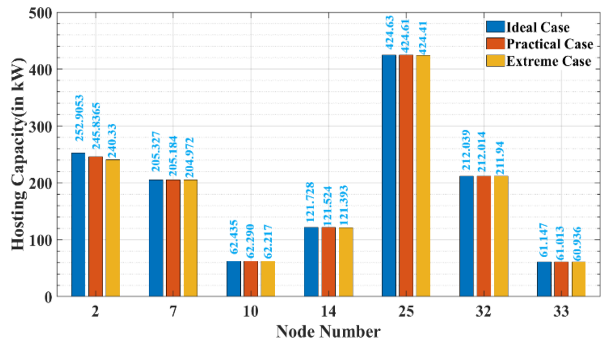

FIGURE 12. Comparative assessment of real-time ODHC estimation over planned HC at different nodes of reconfigured IEEE-33 bus active distribution system.

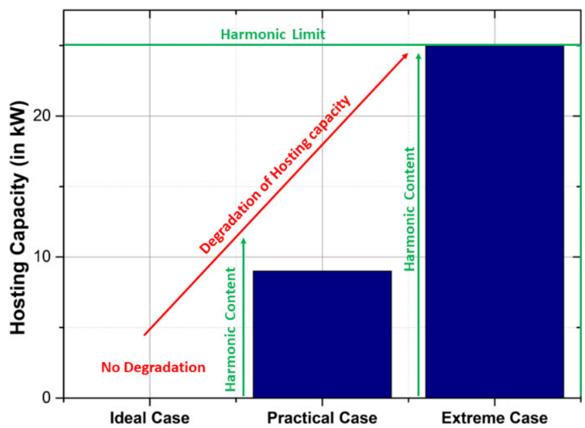

FIGURE 13. Comparative assessment of real-time ODHC estimation over planned HC of reconfigured IEEE-33 bus active distribution system.

injection of harmonics can be witnessed for both the practical and extreme cases, which are observed to be 62.15 kW and 63.431 kW respectively causing a difference in loss of 1.281 kW. Comparison of these two cases is carried out due to fact that practical scenario is most appliable condition for all distribution system. With inclusion of harmonics in the distribution system reactance increases, hence the voltage profile of the network degrades, which causes the flow of higher line current in the network. This higher current contributes to more losses, which is showcased in figure 14.

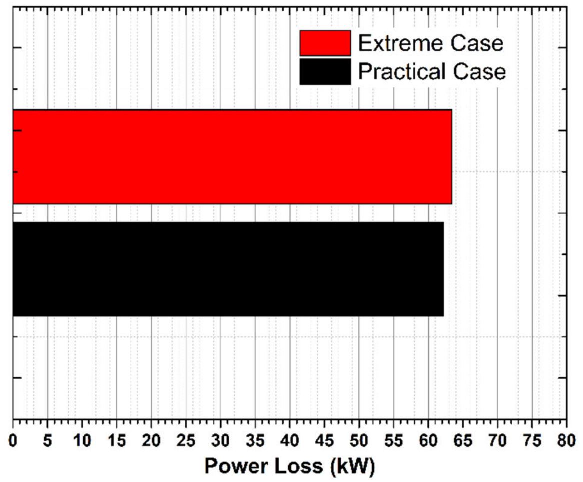

FIGURE 14. Power loss in reconfigured IEEE-33 bus active distribution network due to presence of harmonics.

To validate the derating of HC and to attain the ODHC caused due to harmonics, as presented in figure 12, voltage across all the nodes is measured for practical case in Typhoon HIL real-time environment and showcased in figure 15.

The measured voltages across all the nodes are found to be within safe operational limits of the ADN. This ensures safe injection in the presence of harmonics. In addition to the practical case, for the extreme case also voltage values are found to be within the specified limits as presented in figure 15. But from figure 15, it is also evident that for high-intensity of harmonics in network, the voltage profile deteriorates across all the nodes within the network. The degraded voltage profile at the nodes causes higher current to flow in the lines of ADN. This higher current contributes to more losses, which is already showcased in figure 14.

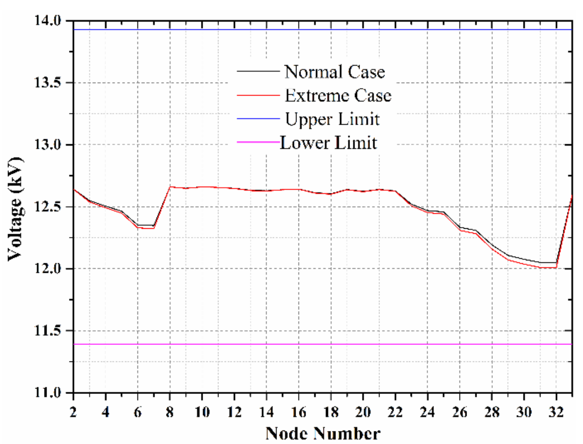

FIGURE 15. Real-time voltage values at different nodes for reconfigured IEEE-33 node active distribution system.

In the ADN there is a possibility of unbalance due to unintentional switching of loads or due to uneven load distribution across the three phases, which compels to study the effect of unbalance on HC derating and estimation of ODHC. The effect of unbalance on HC is also analysed in table 2. Although the DSO always tries to maintain the unbalance to the bare minimum level through various technical as well as behavioral trends, but at some instant it is possible that unbalance may be significant. So, it becomes essential for DSO to analyse the unbalanced condition. To observe and analyse the adverse effect of unbalance on HC estimation, in this work maximum 15% unbalance in load across all the nodes with integrated loads is considered in ADN. It is already observed in figure 9 that the effect of unbalance has an adverse effect on the DPI. It is clear that due to unbalance, the DPI increases, and is found to be higher than the ideal as well as practical case. While this analysis is performed, the voltage unbalance is also considered according to IEEE standards [33], [34].

On comparing the HC in unbalanced case (in Table 2) with the results shown in Figure **12**, it can be observed that the unbalanced loading diminishes the HC of the network, which can be observed from table 2. The derating for unbalanced case is found to be about 8.2 kW cumulatively across all considered nodes, with maximum 4.8% deviation in voltage profile over ideal case.

TABLE 2. HC analysis for practical scenario unbalanced condition.

Node	HC (kW)	Node	HC (kW)
2	245.4933	25	424.5991
7	205.177	32	212.0067
10	62.29	33	61.00997
14	121.5216		

From table 2, it can also be noted that with increasing harmonics the HC capacity gets reduced. It is worth noting that the ODHC for unbalanced case is less than the balanced case, but higher than the extreme case which can also be seen in figure 12. This vital observation on HC estimation is required by the DER installing agencies/prosumers, and DSO to evaluate and control the power injection, when the network is subjected to variable harmonics injection. The above discussion can be summarized as the following observation as presented in equation (10).

$$HC_{Ideal} > HC_{Practical} > HC_{Unbalance} > HC_{Extreme} \quad (10)$$

VI. COMPARISON OF PROPOSED OPERATIONAL DERATED HOSTING CAPACITY ESTIMATION METHOD WITH EXISTING METHODS

A detailed comparison of the proposed ODHC estimation method with the available literatures are discussed and tabulated in table 3, for HC maximization under varied order harmonic content present in ADN. It can be noted from the table 3 that harmonic mitigating devices are mostly used to filter out the harmonic contents from the ADN to improve the power injection as in [12], [13], [14], [15], [16], and [18]. In [19] network reconfiguration is proposed, but additional CBs may be required to optimally reconfigure the network, which is a major drawback. In [20], although no additional

TABLE 3. Comparison of ODHC method with available literatures.

Sl. No.	Ref.	Strategy Applied	No External Device Requirements	No Requirement of Tuning of parameters	ODHC calculated considering harmonics	RT-Validation
1	[12]	GA+ DHPF	×	×	×	×
2	[13]	C-type Filter Design	×	×	×	×
3	[14]	Filter size optimization with GA	×	×	×	×
4	[15]	3rd order damped filter optimization using Pareto-based multi-objective firefly algorithm	×	×	×	×
5	[16]	Adaptive bacterial foraging optimization for placement and size selection of passive filter	×	×	×	×
6	[18]	Network reconfiguration using non-dominated sorting genetic algorithm II and fuzzy decision-making	×	×	×	×
7	[19]	PSO	✓	×	×	✓
8	[20]	Conservative model for HC estimation	✓	×	×	✓
9	Proposed	ODHC	✓	✓	✓	✓

CBs are required, but THD is considered only as an indicator, and the derating due to the presence of harmonics is not calculated in this work. But the ODHC estimation method considers all the power system parameters that are affected by harmonics and their contribution to re-estimate the HC of ADN. It is to be noted that re-estimation of the degraded HC can be done in very less time; ODHC is found to be reliable, computationally more efficient with no additional device requirement. The methodology is also validated in real-time environment to justify its efficacy. It is to be noted that the accuracy of this method depends on the estimation of the harmonics in the distribution network in accordance with IEEE-519 requirements. These measurements need to be propagated to the central control center for calculation of ODHC, which requires strong communication networks. This may limit the efficacy of the proposed strategy.

VII. CONCLUSION

Integration of DERs into the distribution network is essential considering the present as well as the future energy demand. In this context PVDG is one of the most vital DER present in the current time, which has witnessed tremendous growth in the last decade. In this work HC of ADN is accurately estimated under the influence of variable harmonic content. To accomplish the objective, a detailed analysis of harmonics is performed on the reconfigured IEEE 33 bus ADN. Effective line impedances are calculated due to the presence of variable harmonic content. These line impedances contribute to change in DPI of each node across the ADN. Additionally, pf is analyzed with variation in harmonic content of ADN along with the bus voltages. With the contribution of these factors, ODHC is estimated, which is more appropriate and practical value of HC. The numerical derating values stated in section IV for the considered test system is 8.2 kW, appear to be relatively low, but it should be noted that for bigger networks with high power ratings, the values will be exponentially high. Simultaneously, the voltage derating is found to be 4.8% which may further drastically degrade, with increase in network size. ODHC estimation is verified in real-time digital simulator, which is in line with the HC estimation using MATLAB. With the proposed ODHC method, possible variation in power injection can be estimated in an accurate way under the influence of diverse harmonic order present in ADN. Lastly, ODHC method is compared with the available literature to infer the advantages upon its utilization, and it can be concluded that the proposed method can be instrumental to the DSO to have an overall HC visualization of ADN, so that the SA regarding power injection adversaries can be easily handled.

The future direction of the proposed work includes, maximization of HC on highly harmonically polluted distribution network, second minimization of harmonics to further maximize the HC of the network. Furthermore, various advanced applications can be derived from this work for reliable power injection in future such as minimization of cost for filter design, over/ under voltage control and dynamic power injection using controller in ADN etc.

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