Examining Impact of Distribution System Characteristics on Transmission Security Assessment of Future Power Systems

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ABSTRACT
The nature and characteristics of distribution systems are changing continuously with the increased penetration of distributed energy resources. With this, the need for examining the transmission and distribution (T&D) interaction while assessing the voltage security has become significant. In much of the analysis and practices reported so far, voltage security assessment studies are performed separately for T&D systems. Thus, a transmission system operator (TSO) is oblivious to the operations and controls taking place at the distribution system (DS) level. Some of the recent studies examine the impact of an active DS on the voltage security assessment of future power systems. However, the effect of various factors like voltage dependency of loads, reactive power capability of renewable energy sources (RES), location of distributed generation units, and network losses on the voltage stability margin (VSM) of transmission system has not been reported comprehensively so far. This paper first theoretically examines the impact of these factors on VSM. Then, to get the more realistic results for VSM, continuation power flow (CPF) is performed in a coordinated fashion including both T&D systems. The simulations show that considering losses, load characteristics dependency on voltage and reactive power limits of RES in a DS for transmission voltage security assessment studies lead to a more rational outcome than when neglected.

INDEX TERMS
Continuation power flow, distributed generation, load modeling, reactive power capability, renewable energy sources, voltage security assessment.

I. INTRODUCTION
The power system is generally demarcated as transmission system (TS) and distribution system (DS), that are connected to each other at certain interfacing nodes. They are usually operated by different entities such as transmission system operator (TSO) and distribution system operator (DSO). Usually, the analysis for each of the system is carried out in a mutually exclusive way where, the other system is either aggregated or equivalenced. This approach is not correct in the entirety because each system misses out on modeling certain finer aspects of the other system. With the changing nature of DSs on account of large number of inverter-based renewable energy sources (RES) [1] and electric vehicles [2], there is going to be a great need for TS to see certain details of active DSs to fine tune important operations. A coordinated approach of analysis with each system sharing granular modeling details with the other would enable analysis as close to reality as possible. Various reports [3]–[5], have been prepared by different groups to investigate the need and feasibility of the coordination between TS and DS, especially with the increased penetration of distributed energy resources in DS. Also, the coordinated operation frameworks are presented in [6]–[8].

Voltage security assessment is one such important analysis that has very well established legacy practices. Generally, the voltage security of the system is assessed by calculating the MW distance from an operating point to the critical loading point defined as voltage stability margin (VSM) [9]. It can be obtained through a continuum of power flow solutions
starting from a base load condition. This process is termed as Continuation Power Flow (CPF) that defines the relationship between receiving end power and voltage at a bus in a system [10]. In past years, various methods have been presented to study the voltage security assessment problem and evaluating critical loading point. In [9], the concept of voltage stability and a unified approach to this problem is described in details. The other works such as [11], [12], present different methods to trace the critical loading point. Conventionally, all these voltage security assessment techniques are employed by TSO treating DS as an aggregated load connected at the TS and DS interfacing bus. On the other hand each DSO separately monitors the voltage security of DS [13], [14].

A. MOTIVATION

With the fast developments in renewable energy (RE) based resources, the DS is becoming an active network that has the capability to provide real and reactive power support locally and to the grid as well. Hence, this derives a need for considering the impact of an active and smart DS on Transmission CPF (TCPF) instead of treating it as a fixed load injection [1].

DSO has a better knowledge of the attributes of various elements in DS and sharing of complete information with TSO may not be agreeable and feasible too, due to (a) privacy concerns of DSOs (b) storage issues of the huge amount of data for TSO. Moreover, solving any operational problem of a power system centrally is a challenge owing to (a) computational complexities of solving a large scale problem (b) different characteristics of TS and DS. This paves the way to carry out a coordinated operation with a limited amount of data exchange between TSO and DSOs such that the privacy of each system remains intact and they are no longer absolutely blind to each other’s operations.

B. PREVIOUS RESEARCH

The need for performing TSO-DSO coordination for various power system operations such as economic dispatch, state estimation, load flow, network expansion planning, energy and reserve market, voltage stability with the evolution of active distribution systems has been well described in the literature [8], [15]–[20]. In this work, impact of active DS on the aspect of voltage security assessment of T&D systems has been mainly discussed. However, a wide range of studies that assess the impact of active DS on integrated power system has been given in the literature that can be categorized as follows:

- In [20]–[24], the methodologies for performing voltage stability assessment for coupled T-D system are proposed. In [22], the methodology for performing distributed CPF with different parameterization schemes to realize the unified load increase, has been presented. While, in [20], authors have highlighted the impact of voltage maintaining capacity of distributed generation (DG) and the electrical distance of DS on VSM evaluation by a TSO is studied. Further, a more detailed analysis has been presented in [21] that shows the impact of low-voltage tripping of DG units on the static voltage stability of an integrated T&D system and proposed a distributed method to perform the same. The reference [23] uses PV curve superimposition approach and emphasizes on the need to develop a realistic co-simulation framework for a reliable VSM of large-scale coupled T&D systems. In [24], an optimization framework to evaluate the influence of active DS on the voltage profile and active losses of unified T&D system is proposed.

- In [24], [25], various control strategies for DGs present in the DS are proposed that can help in providing voltage support to transmission system. In [25], authors have focused on distributed control schemes of DGs present in distribution system that can aid in increasing the voltage stability and loadability limit of a bulk power system. While in [24], the authors have highlighted the importance of applying control strategies in DG sources to provide voltage stability support for both distribution and transmission network whenever required and minimizing the network losses.

- The different DS parameters considered so far for the analysis are electrical distance of DS, voltage maintaining capability of DG units, and low-voltage tripping of DG units.

Given this scenario, it becomes necessary to study the other DS associated aspects that can affect the voltage security assessment of an integrated T&D system and have not been considered in the past. These factors remain unnoticed by the TSO while performing CPF and that can result in misleading VSM values. This paper fills the gap of proposing various methodologies for performing voltage security assessment studies in a coordinated fashion among T&D system operators and the parameters needed to be considered in these studies to evaluate VSM, and consequently strengthening the concept of TSO-DSO coordinated studies.

C. CONTRIBUTIONS

This paper is about incorporating certain important features of active DS that can affect the VSM calculation studies carried out by TSO, making VSM much more realistic. Extending the work done in recent years, this paper presents a study examining how the characteristics of various components of an active DS can affect the VSM evaluated by a TSO. A Coordinated Continuation Power Flow (CCPF) calculation is proposed to assess the VSM, which takes into account the enhanced modeling of DS. The dependency of load on voltage will change the net loading of DS that eventually changes the pattern of CPF solution points [26], [27]. The modeling of reactive power limits of RES as per the capability curve is also an important aspect as RE based DGs (e.g., solar PV) are connected through a power electronic converter and can provide reactive power support locally [28], [29]. Also, the network losses and net power drawn by DS are influenced.
by DG’s location [30], [31] and seasonal changes in line parameter (R/X ratio) [32]. Thus, the VSM of a network may expand or shrink in comparison to the case where constant power loads/reduced order model for external system with equivalent load exponents [33] and fixed reactive limits/unity power factor were assumed [31], and the DS losses are ignored. Therefore, it is required that there should be an appropriate data exchange between DSO and TSO to obtain a more rational outcome of the analysis. The study presented in this paper strengthens the idea and need of coordination between TSO and DSO.

It is noteworthy to mention that rather than extending well researched area of voltage security studies pertaining to VSM calculation, this paper proposes a mechanism that paves way to accommodate certain intrinsic features of modern and future DSs to establish a realistic VSM. The main contributions of this work are:

- to evaluate a more pragmatic value of VSM using transmission-distribution coordination
- to analyze the impact of much neglected influencing factors like (a) voltage dependency of DS loads (b) reactive power capability of RES on VSM
- to examine the effect of change in network losses due to DG placement and at varied R/X ratio of DS on VSM.

The backbone behind realizing this idea is facilitating TSO-DSO coordination with limited data exchange that leads to CCPF framework.

D. PAPER ORGANIZATION

The formulation of power flow equations to perform CCPF is described in Section II. Various factors influencing the VSM of a system are discussed in Section III. The methodology to do CCPF is given in Section IV and results are presented in Section V. Conclusions are delineated in Section VI.

II. PARTITIONED SYSTEM FOR VOLTAGE SECURITY ASSESSMENT

To perform the voltage security assessment, the entire power system can be divided into three parts for the ease of analysis as Transmission (T), Distribution (D) and Boundary (B) systems as shown in Fig. 1. The boundary-system buses (BBs) are the interfacing buses of T-D system that represent points of common connection. All the buses in transmission and distribution systems excluding BBs compose the T and D systems, respectively. There can be ‘N’ number of DS connected to the TS via different BBs. While performing individual power flow and voltage security studies for TS and DS, BB acts as a load bus for TS and as a reference bus for DS.

The parameterized power flow equations for each subsystem can be represented by (1)-(3) where λ is the scaling factor of load at a certain operating point [20], [21].

\[
S^g_T (X_T, \lambda) - S^d_T (\lambda) = S_{TT} (X_T) + S_{TB} (X_T, X_B),
\]

\[
S^g_B (X_B, \lambda) - S^d_B (\lambda) = S_{BT} (X_T, X_B) + S_{BB} (X_B) + S_{BD} (X_B, X_D),
\]

\[
S^g_D (X_D, \lambda) - S^d_D (V_D, \lambda) = S_{DD} (X_D) + S_{DB} (X_B, X_D).
\]

The vector of state variables for each system is given by \( X = [V, \theta] \). For system \( J \), \( S^g_J \) denotes the net power generation and \( S^d_J \) denotes the net load, while \( S_{JJ} \) represents the line flows within the buses in system \( J \). \( S_{JK} \) represents the line flow from a bus in system \( J \) to a bus in system \( K \). \( S^g \) and \( S^d \), both are functions of loading parameter \( \lambda \).

\( S_{DB} \) represents the net power drawn by DS from TS at the BB. Hence, \( S_{BD} = -S_{DB} \) can be represented as an aggregated DS load for TCPF. These equations can be used to determine the states of the entire power system at varying loading conditions. Subsequently, the critical loading point can be traced. This is the conventional model of the system to carry out voltage security assessment studies, reconfigured to separate out BBs and expanded to include distribution systems.

III. DISTRIBUTION SYSTEM CHARACTERISTICS AND IMPACT ON VSM

The impact of DS load modeling, losses and RES reactive power capability, their location on VSM is examined in this section.

A. LOAD MODELING (LM)

In general, loads are specified as a constant active and reactive power values at TS level. However, DS consists of industrial, residential and commercial loads that are dependent on voltage. In the presence of the various combination of load models, the power flow solution gets affected significantly [34]. The term \( S^d_J (V_D, \lambda) \) in (3) represents the voltage dependent characteristics of DS loads. The real and reactive load for the \( i^{th} \) bus in a DS can be expressed in the exponential form as:

\[
P_{di} (\lambda, V (\lambda)) = P_{di0} (1 + \lambda) \left( \frac{V_i}{V_n} \right)^{n_{pi}},
\]

\[
Q_{di} (\lambda, V (\lambda)) = Q_{di0} (1 + \lambda) \left( \frac{V_i}{V_n} \right)^{n_{qi}}.
\]

where \( P_{di0} \) and \( Q_{di0} \) represent the active and reactive loads at nominal voltage \( V_n \) and \( \lambda = 0 \). \( V_i \) is the magnitude of voltage at \( i^{th} \) bus. The values of exponents \( n_{pi} \) and \( n_{qi} \) for real and reactive power respectively, at each bus can have a wide range and their values are selected as per [35]. It is worthwhile to note that it is DSO, who has better information of its load composition than the TSO. Thus, even if the TCPF

**FIGURE 1.** Schematic diagram illustrating the integrated power system.
is performed by assuming a reduced order model of DS with equivalent load exponents connected as a load at BB (say TCPF-LM), VSM can be overestimated or underestimated.

As the load \(P_{di}\) is a function of \(\lambda\) and the network voltage \(V_i\) and \(V_i\) itself is a function of \(\lambda\) such that with the increase in the voltage, the voltage reduces \[10\], providing the voltage dependency of load cannot be neglected. The effect of voltage dependent load modeling on VSM is explained in Fig. 2(a) that shows the variation of \(P_{di}\) with the loading parameter \(\lambda\) for \(i^{th}\) bus in a system having voltage dependent load. The three curves correspond to different value of load exponent \(n\). It can be observed that load can be increased to a certain value of \(\lambda\) which is called a critical loading point of that bus \(\lambda_c\). Beyond that point, even if \(\lambda\) is increased, the load power reduces because the rate of decrease in voltage is more dominant than the increase in \(\lambda\).

While Fig. 2(b) shows the PV curve for the same \(i^{th}\) bus. At the point '4', \(\lambda_4\) corresponds to maximum value of loading parameter \(\lambda_m\). However, load increases only till point '3' and beyond that it starts reducing, thus making \(\lambda_3\) as \(\lambda_c\) of that bus. Thus, if the system is operating at base load condition (point '1'), then point '3' defines the VSM of the corresponding bus. As shown in (4) and (5), the load is a function of two variables but only \(\lambda\) is an independent variable. Thus, the maximum loading of the system \(P_{di}^{max}\) can be calculated by solving \(\partial P_{di}/\partial \lambda = 0\)

where \(K = V_i/n_{pi} (1 + \lambda)\). It can be inferred from (7) that the point of maxima is reached when the change in voltage becomes equal to \(K\) times the change in \(\lambda\) in two consecutive steps of load growth. Therefore, \(\lambda^c\) in the \(k^{th}\) step gives the value for critical loading for \(i^{th}\) bus as per (8).

\[
\left( V_i - V_i^{k-1} \right) = \frac{V_i^{k-1}}{n_{pi} (1 + \lambda^{k-1})} (\lambda^k - \lambda^{k-1}).
\]

\(K\) can be different for each bus as it depends on bus voltage and the load exponent value. For voltage dependent loads, the value of exponent \(n\) \(n_{pi,n_d}\) is greater than 0 and with the increase in \(n\), a notable change will occur in \(\lambda_c\) as \(K \propto 1/n\), shown in Fig. 2(a). The value of \(\lambda_c\) will increase with the increase in voltage dependency of loads \[26\], \[27\]. Consequently, the value of maximum real load at the critical point \(P_{di}^{max}\) will be different in comparison to that for the constant power load (for \(n = 0\), \(P_{di}\) is independent of the decrease in voltage). Hence, considering load modeling at a more granular level (i.e., at DS loads level) will help in evaluating the actual VSM for each bus of the network which may be a higher or lower value than the one obtained by assuming a constant power or an equivalent load model at the same bus.

Remark 1: It is important to note that due to the voltage dependency of load characteristics, \(\lambda_c\) need not be necessarily \(\lambda_m\). From the practical point of view, it is the MW distance from an operating point to voltage collapse point (at \(\lambda_c\)), that defines VSM. As different buses in a system have different base case loading and load characteristics, their MW distance to point of voltage collapse may differ. This is unlike the thinking in legacy practice where all loads in a system are considered as constant power and P-V curve is similar to \(\lambda-V\) curve.

B. ROLE OF INTERCONNECTING TRANSFORMER

The role of an interconnecting transformer at the substation is to regulate the voltage of secondary bus, which is further treated as a reference bus for DS. Carrying out voltage security assessment studies with constant power load modeling is attributed to the assumption of transformer’s secondary voltage restoration through Load Tap Changers (LTC). However, this assumption does not hold good on various accounts. First, considering the life of a physical asset, the number of tap changing operations in a day is limited. Further, the tap changers operate in a stepped fashion rather than continuous. Secondly, under the stressed conditions, LTC may hit its limit, where the secondary of a transformer starts following primary voltage. It is for these reasons that the voltage dependency of loads needs to be incorporated in voltage security assessment studies, and the same can be contemplated through TSO-DSO interaction.

C. REACTIVE POWER CAPABILITY OF RES

Generally, RE based DGs (e.g., solar) are connected through a power electronic converter to the DS \[28\], \[29\] that have capability to provide real and reactive power support locally.
and to the main grid. Reference [1] focuses on the significance of considering the impact of RES at transmission level and presents their aggregated modeling at the substation. However, it has been also stated that the equivalenting at substation level is generally not recommended for high RE penetration scenarios as the models can be misrepresented. Thus, TSO-DSO interaction can aid in determining the potential impact of RES. Usually, these resources are operated at unity power factor or the fixed reactive power limits are considered. But they can be made to operate at some power factor to derive further benefits.

Consequently, the reactive capability of RES can have a prominent effect on VSM of the system. For a defined value of active power $P_{DG}$ produced by RES, the constraints on reactive power are imposed by the limits on converter current and voltage. The limitation on maximum converter current restricts the maximum reactive power absorption capability while the limitation on maximum converter voltage restricts the maximum reactive power injection capability of RES. Hence, the $Q$ limits can be written as:

$$Q_{\text{min}} = \sqrt{(V_{DG}I_{\text{c, max}})^2 - P_{DG}^2}, \quad (9)$$

$$Q_{\text{max}} = \sqrt{(V_{DG}I_{\text{c, max}})^2 - P_{DG}^2 - \frac{V_{DG}^2}{X_c}}, \quad (10)$$

where $V_{DG}$ is the terminal voltage that RES is supposed to maintain at the bus by absorbing or injecting the reactive power. $I_{\text{c, max}}$ is the maximum value of converter voltage and $I_{\text{c, max}}$ is the maximum current rating of the converter as described in [36]. $X_c$ is the total equivalent reactance of converter.

It can be followed from the above equations that $Q_{\text{min}}$ is independent of $X_c$ while $Q_{\text{max}}$ is more for smaller values of $X_c$. Also, it is worthwhile to note that, Q limits will no longer remain constant for a RES. It varies with $P_{DG}$ at different time of the day (TOD) and with seasonal variations. As per (9) and (10), Q limits will shrink or expand with high or low solar penetration, respectively.

Further, the effect of reactive capability of RES on VSM can be explained with the help of a two-bus system shown in Fig. 3(a). Let bus 1 be a reference bus with $1\angle 0^\circ$ voltage. At bus 2, there is a load $P_{d2} + jQ_{d2}$ and a RES that generates $P_{G2} + jQ_{G2}$. The buses are connected through a line with admittance of $y = g + jb$. As per the analysis presented in [21], if the load is increased till the critical point is reached, then the maximum load values $P_{dc}$ and $Q_{dc}$ should satisfy the following parabolic equation defined by curve ‘C’:

$$C : Q_{dc} = Q_{g2} + \frac{b}{4} - \frac{(P_{dc} - P_{g2})^2}{b}, \quad (11)$$

with the intercepts on $P_{d} - Q_{d}$ axis as follows:

$$x_c = P_{g2} + \frac{b}{2}\sqrt{1 + \frac{4Q_{g2}}{b}}; \quad y_c = Q_{g2} + \frac{b}{4} - \frac{P_{g2}^2}{b}. \quad (12)$$

Generally the per unit value of $P_{g2}$ is much smaller than $b$, hence $Q_{g2} > P_{g2}^2/b$. It can be inferred that for higher values of $Q_{g2}$, the curve will shift upwards ‘$C_1$’ and for lesser value the curve will shift downwards ‘$C_2$’. If we assume that the load has started increasing from base case load point $(P_{d0}, Q_{d0})$ along the direction of line OD, then the intersection of line OD with curves ‘$C$’, ‘$C_1$’, and ‘$C_2$’ will give the maximum loading of system i.e., $\lambda_1$, $\lambda_2$, and $\lambda_3$, respectively as illustrated in Fig. 3(b). Therefore, the change in the capability of a RES to provide reactive power at different TOD will influence the loadability limits of a system.

**D. DISTRIBUTION SYSTEM LOSSES**

Conventionally, a TSO looks at DS as a fixed load which is an estimated value of power requirement provided by a DSO. The value of BB injection in practice depends on the network losses and DS net loading. The network losses are influenced by multiple factors like seasonal variations, DG’s location, etc. Any change in loss under various operating conditions will alter the net injection at BB and inevitably affect the VSM of a system. Some of these factors are discussed below:

1) SEASONAL VARIATIONS CHANGING R/X RATIO OF DS

The R/X ratio is an inherent characteristic of a network and remains same for a given conductor material, size and spacing between the conductors. But R can vary dynamically with the ambient temperature. The impedance value for different types of cables and at various ambient temperature is presented in [37], which reflects the variation of R with change in weather conditions and thus changing R/X ratio of the network. The change in resistance of lines seasonally will directly affect the system losses.

2) PLACEMENT OF DGs IN A DS

DG placement has a prominent impact on the operation of DS such as system losses, voltage profile, reliability of power supply, and capital and operating cost. In [30], [31],...
an overview of various methodologies for optimal placement of DGs is presented. Albeit, in some cases, the DSO has no control over DG location and size. The decision is taken by their owners. Thus, in such cases, it becomes difficult to estimate losses and net power drawn by DS from grid.

Remark 2: The discussion so far reveals that the amount of power drawn by DS from TS will change the VSM of system and the primary reasons for the same are: (a) net loading that varies due to the DS load dependency on voltage (b) RE penetration level (c) the role of RES’s reactive power capability (d) network losses that vary with DG placement and line parameters. Here, the resistance of cables is dependent on ambient weather.

IV. COORDINATED CONTINUATION POWER FLOW (CCPF)

The methodology to perform CCPF and the evaluation of VSM is presented in this section.

A. METHODOLOGY

The essence of whole proposal is to perform each step of predictor-corrector in CPF in a sequential manner on both TS and DS, to make it a coordinated CPF in order to determine the accurate MW distance to voltage collapse point. The predictor step is generally performed only for TS to get the estimation of subsequent solution for the new value of λ. While, the corrector step is performed individually for TS and DS, that corrects the estimate and gets the exact state of system for new loading. The BB is considered as a part of TS. The entire procedure for CCPF is summarized in Algorithm 1.

Algorithm 1: Coordinated Continuation Power Flow

Result: Voltage Stability Margin, λc

begin
Step 1: Perform coordinated base case power flow

Initial condition: VB = 1 pu, λ = 0
Solution: XT = [V0T, θ0T], SBD

Step 2: Perform Predictor step for TS

Initial condition: XT
Solution: X1T = [VT1, θ1T] and λ

Step 3: Perform coordinated corrector step

while |ΔST| < ϵ do

Run TS power flow: solve (1)-(2)

Initial condition: XST, λ, SBD
Solution: VB;
Run DS power flow: solve (3)

Initial condition: VB, λ
Solution: SBD;
end

Output: XST = [VC, θC]

Step 4: Update XT = XST and go to Step 2. Continue till λm, λc are obtained.
end

Firstly, the base case power flow of T-D system is performed in a coordinated fashion with an initial input of BB voltage as 1 pu [38] and λ = 0. At the obtained solution point (V0T, θ0T), the TS predictor step is performed by solving an augmented power flow equation to get a tangent vector in the direction of solution path. The solution obtained is multiplied by a small step size value to get an updated loading parameter λ and system state variables (VT1, θ1T). Next, the predicted value is corrected using coordinated power flow for T-D systems. Firstly, conventional Newton-Raphson power flow is run for TS with an initial guess of state variables as predicted values (VT1, θ1T), solving (1)-(2). Then the values for BB voltages and lambda (VB, θBB, λ) are passed to DS, where power flow is performed i.e., solving (3). The injections from BB to the DS (SBD) are then passed back to TS. This coordinated corrector process continues until the TS power flow converges. The tolerance value (ε) assumed is 0.00001. Further, these values (VT1, θ1T) are given as input to the TS predictor step to find the next solution point for an increased loading value. Consequently, the state of T-D system is determined for different loading values and the MW distance between operating point and voltage collapse point i.e., VSM is evaluated.

Here, at each iteration of the coordinated corrector step, the Q limit violation of a RES is checked. If limit is reached, then PV to PQ switching is done for RES connected bus and Q is set as the updated value of Qmax or Qmin. Also, at each iteration the DS power flow considers the effect of change in voltage and λ on load, losses and RES’s reactive power injections.

B. EVALUATION OF VSM

With the above algorithm, the value of VSM obtained by calculating the maximum loading PBD,k of kth BB for three different approaches (considering LM factor) can be defined as follows:

1) TCPF: power required by a DS at base case is connected as a constant power load at BB
2) TCPF-LM: it is assumed that TSO has knowledge about an equivalent load exponents representing DSs’ load characteristics, thus power required by a DS at base case is connected as a voltage dependent load at BB
3) CCPF: net power requirement by DS is communicated by DSO

The empirical expressions for knee point of PV curve obtained from various approaches can be defined as follows:

\[ P_{BD,k}^{max,1} = \left( \sum_{i\in D} P_{d0} - \sum_{i\in D} P_{DG} \right) \left( 1 + \lambda_c \right) \] (13)

\[ P_{BD,k}^{max,2} = \left( \sum_{i\in D} P_{d0} - \sum_{i\in D} P_{DG} \right) (V_k)^{\gamma_{PS}} \left( 1 + \lambda_c^2 \right) \] (14)

\[ P_{BD,k}^{max,3} = \left( \sum_{i\in D} P_{d0} (V_i)^{\gamma_{PS}} \right) \left( 1 + \lambda_c^3 \right) - \sum_{i\in D} P_{DG}. \] (15)

The first two approaches essentially depict the conventional way of doing things. From (13)-(14) it can be noted that
\( P_{BD,k}^{max} \) can be greater or lesser than \( P_{BD,1}^{max} \) depending upon the value of \( V_k \) and \( \lambda_c \). However, as the value of \( n_{pk} \) is derived on the basis of certain assumptions, the TCPF-LM approach does not guarantee the accurate solution either. While in Case 3, DSO reflects the actual operating conditions of a DS taking into account the voltage dependency of load at each node. Equation (15) shows that the load seen by TS at BB while performing CCPF will be significantly different from Case 1 or Case 2 for all values of \( \lambda \). It is dependent on the voltage and load exponents of each DS node \((i)\). Eventually, this will impact the value of VSM of \( k^{th} \) BB that will be different than the one calculated using TCPF. However, other factors will be also considered in CCPF that will impact the VSM. Thus, the expressions (13)-(15) illustrate the impact of different parameters on the value of VSM and how the difference in the outcome of each approach emerges.

V. CASE STUDIES

Two integrated T&D systems are constructed by connecting a single feeder 33 nodes DS [39] to IEEE 14 and 30 bus systems [40], at two different BBs. The test systems are named as T14D2 (BB1:10, BB2:12) and T30D2 (BB1:15, BB2:19). Fig. 3(b) shows an illustration of test system T14D2. The study is carried out for primary distribution system thus, balanced DS is considered. The distribution systems, DS1 and DS2 are connected at BB1 and BB2 of TS, respectively. Some of the load buses of TS are selected as BBs. The actual loads connected to the BBs are replaced by the DS. To match the net BB injections with the actual loads of IEEE transmission systems, DS loads are scaled up/down. Each DS contains three units of solar power based RES and voltage dependent loads as shown in Fig. 4(b). For the assessment of voltage security of the integrated system, the load and generation have been increased proportionally to the base case values for both TS and DS. The assumed MVA base is 100 and step length is 0.01. For the reasons stated earlier, DS needs to follow the voltage of primary side TS bus as a reference.

Here, conventional TCPF is performed by assuming net power drawn by DS connected as a constant power load at BB. This power is calculated using load flow at the base condition for all the scenarios discussed in the following subsections.

A. IMPACT OF VOLTAGE DEPENDENT LOAD MODELING ON VSM

The \( \lambda - V \) curves for BB of both test systems for TCPF and CCPF along with the value of \( \lambda \) at the nose point is shown in Fig. 5. Further, the comparison of PV curves for BBs and non-BB has been done for TCPF and CCPF as shown in Fig. 6 and Fig. 7. The value of \( \lambda_c \) and \( \lambda_m \) as per Fig. 2(b) for CCPF method is also marked. Solar penetration is assumed to be at 80%.

1) OBSERVATIONS

The following observations can be made from the results obtained:

- The inclusion of LM has shifted the \( \lambda - V \) curve towards the right as depicted in Fig. 5.
- But the critical loading point \( (\lambda_c) \) obtained from CCPF as per PV curve is different from \( \lambda_m \) of CCPF and \( \lambda_c \) of TCPF, as shown in Fig. 6.
- Also, the \( \lambda - V \) curves are same as PV curve for non-BBs (because their loads are not voltage dependent) while they are different for BBs as can be seen from Fig. 5-7, confirming the theoretical analysis presented in Section 3.1.
- From Fig. 6, the lower value of \( \lambda_c \) indicates the occurrence of voltage collapse point of BB at higher voltage magnitude but the higher \( P_{BD}^{max,3} \) reflects an increase in
loadability limits. Thus, for such cases, the improvement in voltage sensitivity of BB to the change in bus loading can be observed.

- The inclusion of appropriate DS load models for voltage security assessment of TS will impact the individual buses MW distance to voltage collapse.
- Thus, it can be concluded that PV curves are the appropriate method to trace VSM for the network while using $\lambda$-$V$ for the same can be misleading in the presence of voltage dependent load models.

2) COMPARISON OF CCPF AND TCPF-LM

Additionally, for the completeness of comparison, a simulation is carried out for the case TCPF-LM, as discussed in Section 4.2. Fig. 8 presents the PV curves for TCPF-LM, TCPF and CCPF for BBs of system T30D2. Here, in TCPF-LM, TSO performs CPF considering the exponent value of aggregated load (representing DS) at BB 15 and 19 as $n_p = 1.0284, n_q = 2.9198$ that is equivalent weighted average value for a DS. This approach avoids the exchange of information among system operators and takes into account the voltage dependency of DS loads [27]. However, the inaccurate realization of VSM due to the approximations involved in calculating equivalent load exponents can be clearly observed from Fig. 8.

3) LARGE SCALE SYSTEM IMPLEMENTATION

To further demonstrate the feasibility of proposed CCPF, it has been implemented on a large scale integrated T&D
system namely, T118Dn4 (IEEE 118 bus transmission system is connected to 4 DSs at the boundary buses 39, 50, 67 and 98) where Dn is a 141 node radial distribution system [40], [41]. Each DS contains four units of solar power based DS connected at the nodes 30, 50, 58 and 125, and voltage dependent loads. The PV curves for TCPF-LM, TCPF and CCPF for BBs and non-BB i.e., 23 obtained from the simulations carried out on T118Dn4 system is shown in Fig. 9. All observations made above holds good for this test system also, thus validates the effectiveness of CCPF over TCPF or TCPF-LM methods for large scale systems as well.

4) BEHAVIOR OF BOUNDARY BUS INJECTION ($P_{BD}$) WITH LOADING PARAMETER ($\lambda$)

Also, the behavior of $P_{BD}$ with the increase in $\lambda$ in CCPF is shown in Fig. 10 for BB and non-BB of all test systems. It can be seen that the critical loading point for BBs is reached earlier than non-BB.

Therefore, if a TSO does not account for the change in DS loading with bus voltage while performing TCPF, the VSM of a system can be misjudged.

B. IMPACT OF Q LIMITS OF RES ON VSM

For having a better understanding regarding the impact of RES’s Q limit modeling (QM), LM is not included in this case study. Thus, $\lambda_c$ will directly define the MW distance to the point of collapse and will be same for all TS buses.

1) RES PENETRATION SCENARIOS

For a non-dispatchable RES, the output power has temporal variations. In this work, the hourly variation of solar power source is taken from [39]. To simulate different RES penetration scenarios (low, medium and high), three hours are selected. Scenario 1: Hour 10, high RE penetration, Scenario 2: Hour 13, medium RE penetration, Scenario 3: Hour 17, low RE penetration. For comparison with the conventional practices, the reactive power limits of RES are kept fixed at $\pm 0.01$ pu and $V_{DG}$ as 1 pu [20].

The values of $\lambda_c$ for TS of system T14D2, T30D2, and T118Dn4 and for all scenarios are compared in Table 1.

2) OBSERVATIONS

The VSM given by TCPF is smaller than CCPF due to the availability of restricted information to a TSO about the RES’s behavior in a DS.

The change in the values of reactive power that a RES is injecting or absorbing is more prominent when the derived
TABLE 1. Values of $\lambda_c$ for TCPF and CCPF with QM.

| Test System | Scenario | RES Penetration level | TCPF | CCPF |
|-------------|----------|-----------------------|------|------|
| T14D2       | 1        | 10 %                  | 0.6246 | 0.6937 |
|             | 2        | 28 %                  | 0.6559 | 0.7108 |
|             | 3        | 62 %                  | 0.7142 | 0.7352 |
| T30D2       | 1        | 10 %                  | 0.9930 | 1.0789 |
|             | 2        | 28 %                  | 1.0298 | 1.0950 |
|             | 3        | 62 %                  | 1.0897 | 1.1143 |
| T118Dm4     | 1        | 10 %                  | 1.3474 | 2.0169 |
|             | 2        | 28 %                  | 1.4329 | 2.0784 |
|             | 3        | 62 %                  | 1.5211 | 2.1125 |

Q limits differ more from the assumed fixed values. Also, the dominance of QM depends on the values of other factors like active power output of RES, the terminal voltage that RES is supposed to maintain and the converter parameters. For the test systems here, the Q limits evaluated from (9)-(10) are higher than the fixed values considered for all scenarios. Value of $Q_{\text{max}}$ in per unit at different penetration levels is given in Table 2. The DS will get enhanced reactive power support locally. Even though with the increase in real power penetration, Q limits shrink, the net real and reactive power drawn by DS from the transmission grid reduces. Hence, the loadability margin of the whole system enhances and the measure of improvement depends on the RE penetration level.

C. IMPACT OF DS LOSSES ON VSM

As discussed in Section 3.4, the impact of DS losses on VSM is analyzed by varying R/X ratio of DS and location of DGs through CCPF scheme (including DS– LM and RES’ QM).

1) R/X RATIO

As a consequence of seasonal fluctuation in ambient temperature, the resistance of line changes. This scenario has been simulated by varying R/X ratio of branches in both DSs of T14D2. The loss value in MW for each DS at different R/X ratio is given in Table 3. PV curves are shown in Fig. 11 for BBs of system T14D2. Here, case A corresponds to the R/X ratio values at standard temperature (denoted as $\delta$) while in cases B, C and D, R/X ratio is increased to realize a rise in temperature. Cases E and F are for drop in temperature where R/X ratio is reduced. It can be observed that higher R/X ratio causing more losses has negative impact on VSM and vice-versa.

2) DG LOCATION

In this work, effect of different DG locations on VSM is considered. Three cases are considered here for the analysis where DGs are shifted from near end to far end of BB.

TABLE 3. Loss in DS (MW) for different R/X ratio.

| Case     | F         | E         | A         | B         | C         | D         |
|----------|-----------|-----------|-----------|-----------|-----------|-----------|
| R/X ratio ($\times \delta$) | 0.3 | 0.7 | 1 | 1.4 | 1.8 | 2.2 |
| DS1 loss | 0.3728 | 0.8877 | 1.2833 | 1.8298 | 2.4025 | 3.0088 |
| DS2 loss | 0.2334 | 0.5513 | 0.7955 | 1.1302 | 1.4767 | 1.8371 |

FIGURE 11. PV curves for (a) BB 10 (b) BB 12 of T14D2 with different R/X ratios through CCPF.

Cases A, B and C correspond to DG placement at nodes (3,19,23), (17,22,32), (12,20,29), respectively. PV curves for BBs in T14D2 for different DG locations are shown in Fig. 12. It can be clearly seen that the DGs placement towards the far end from BB, improves the VSM of a system, for the reasons stated in Section 3.4.

D. OBSERVATIONS

- The less accurate realization of VSM for TCPF or TCPF-LM due to the approximations involved in calculating an equivalent of DS can be clearly observed from the results.
- The maximum loading point for a transmission system ensuring the voltage security, assessed through CCPF and TCPF or TCPF-LM differs notably. The primary reason is that TSO only knows the base case BB injections, and ignores the following:
  - losses occurring in DS on account of network parameters and DG’s location
  - capability of intermittent RES to inject real and reactive power
  - voltage dependency of loads with the increase in loading.
This will impact the net real and reactive power drawn by DS from the transmission grid. This may exaggerate or understate the VSM.

- Even, TCPF-LM leads to an inaccurate realization of VSM due to the approximations involved in calculating equivalent load exponents.
- PV curves should be the preferred way to trace VSM for the transmission network primarily in the presence of voltage dependent loads.

Thus, it can be concluded that the proposed CCPF approach makes a better voltage security assessment in comparison to the conventional approaches such as TCPF or TCPF-LM.

E. APPLICATION OF CCPF TO LARGE SCALE SYSTEM AND LIMITATIONS

All the simulations were carried out on a PC running MATLAB 2017b with Intel Core i7, 3.41 GHz, 16 GB of RAM. It takes between 8-10 iterations for each corrector step and 4.18 seconds for T14D2 test system to obtain a converged solution. While, for T118Dn4 test system, it takes between 18-20 iterations and 14.65 seconds, for various cases. Though the number of iterations and time taken would increase with the size of system in CCPF, the fact that very less time is required for combined TS-DS calculation and that the simultaneous communication of all DSOs with TSO is being done, feasibility of the proposed approach for large scale systems gets established. Further, the computational burden is significantly less than the centralized approach as each entity performs its independent operation with a minimal exchange of data at the boundary bus.

One of the major challenge associated with this approach is the establishment of a secured communication medium for coordination between TSO and various DSOs. Perhaps, the switching from CCPF model to TCPF-LM model may be invoked in such cases.

VI. DISCUSSION AND CONCLUSION

This paper provides more insight into the impact of certain features of active distribution systems on the calculation of VSM. For this purpose, a coordinated continuation power flow method is proposed. The theoretical analysis has been done to show the impact of DS losses, voltage dependency of loads and reactive power capability of RES on the loadability limits of the system. The results of various simulations demonstrate that the location of DG, variation in line parameters with seasonal weather fluctuations and the reactive support provided by a RES impact the DS losses. Further, the net load of DS alters with the system voltage. All these factors amend the amount of real and reactive power drawn by the DS from the TS significantly which consequently affects the MW distance from an operating point to the voltage collapse point of a system. The practice of modeling the DS as an aggregated load at a BB will make TCPF unable to reproduce the actual operating conditions of DS. Thus, the incorrect evaluation of critical loading point using TCPF may lead to false alarming. Therefore, it is vital to adopt the proposed CCPF method to calculate a more reliable VSM of the integrated power system in a coordinated manner with a limited sharing of data between TSO and DSO.

It is pertinent that regulations and network codes must be framed in order to facilitate the coordination between TSO and DSOs for the data exchange, usage of communication infrastructure, and data management while implementing the coordinated methodology on a real-life large scale power system. Also, new grid codes are needed to be defined for utilizing the voltage support capabilities of RES. Moreover, the proposed analysis can be extended to the secondary level and unbalanced distribution system models can be included. However, the discussion on these issues is currently out of the scope of this paper and can be addressed in future work.

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