Method to Improve Voltage Stability Using Flexible Resources

Engr. Muhammad Tawqeer

Faculty of Engineering & Technology

Gomal University Dera Ismail Khan, Pakistan

Email: muhammadtawqeer800@yahoo.com

Abstract

Voltage stability margins of modernbulk power systems are significantly suffering from renewable energy sources (RESs). The intermittency of those units can constantly move the critical location driving the system to voltage collapse along different coherence regions. Traditional approaches weren't designed to affect this scenario, typically providing a centralized actuation supported a system-wide perspective. during this sense, this *paper proposes a completely unique area-based outlook to require advantage of the new possibilities enabled by power systems distributed controllable resources, e.g. flexible resources, to tackle this critical operational challenge. For this sake, a completely unique area-based sensitivity index, exploring both the network- wide sensitivity and therefore the local characteristics of voltage collapse is proposed to work out the foremost effective buses for voltage support and their respective capability of accelerating the system's load margin. Comparative case studies indicate the superior capability of the proposed direct method to affect the new perspectives of recent power systems.*

Keywords

Modernbulk power system, Flexible resources.

1. Introduction

Securing a secure voltage stability margin is one among the foremost critical aspects in guaranteeing the reliability of power systems [1]. Traditionally, the specified voltage stability margins were achieved using VAR compensating devices; e.g., static VAR compensators (SVC) [2]. These components were typically allocated at the network's most critical nodes as identified by a system-wide sensitivity analysis [3]. However, this will cause overcompensation in specific system regions; because the identified critical nodes tend to be on the brink of each other [3]. Moreover, as power systems move towards an increased penetration of renewable energy sources (RESs), these approaches may not be efficient, since the variable and unsure generation of such resources can significantly affect the system static stability margins [2–4] and may continuously move the start line of voltage collapse across different regions of the system. On another avenue, recent developments in monitoring and control have been resulting in a pronounced improvement in power grid flexible resources capacity [5], including the utilization of energy storage systems (ESS), distributed generation (DG),electric vehicles (EVs) and demand response (DR) to provide load flexibility. The use of such flexible resources to enhance several network aspects (e.g., unit commitment, peak shaving, and cargo shifting) has been recently investigated within the literature [5,6]. during this perspective, this paper revisits the voltage stability problem proposing a completely unique adaptive area-based voltage stability index which will be used along side flexible resources to make sure a secure voltage stability margin under varying renewable energy sources (RES). The proposed index avoids overcompensation in specific system regions, and consequently early saturation of the voltage stability margin improvement capacity, by adaptively determining the network most crucial cores and areas considering the changes in RESs generation. to the present end, first a network-wide sensitivity analysis is performed to supply a general perspective of the system voltage stability. Next, the local characteristics of voltage collapse are explored, resulting in the calculation of the proposed area-based sensitivity index. This index can directly determine the foremost efficient locations and their respective capability to improve the system voltage stability. Flexible resources are then used at these locations to supply the specified voltage support.

2. Literature Review

Voltage stability has been continuously under investigation within the facility system industry and academic community given the magnitude of its consequences and direct association to major blackout events worldwide [2]. An outsized body of research work has been dedicated to the assessment of power grid voltage stability, including seminal works as continuation power flow methods related to P-V curve analysis [7], L-index [8], singular value of the load flow Jacobian [9], tangent vector [10] and voltage collapse proximity indicator (VCPI) [11]. additionally, new indexes were recently proposed considering the novelpower systems perspectives. The work developed in [12] presents a replacement voltage stability index supported power flow di- vergence and decay of voltage magnitude. The study in [13] proposes a replacement P-index ready to indicate the steady- state distance to voltage col- lapse, also as dynamic voltage stability. Next, in [14] submodular optimization is explored as a tool to prevent voltage instability. Whilst [15] seeks to mitigate the danger voltage stability taking advantage of the rise observability provided by PMUs. Based on these works, several methods are proposed seeking the development of power systems' voltage stability margins through the insertion of compensation devices. In [16] a technique supported the bifurcation method is employed to work out the optimal location, control and appropriate sizes of SVCs and thyristor- controlled series compensation (TCSC) to avoid voltage collapse. The add [3] uses the system-wide voltage stability perspective provided by the tangent vector to work out the foremost critical locations for reactive power compensation. Heuristic solutions supported genetic algorithm are explored by [17] and [18] considering transmission lines loadability constraint and therefore the L-index as optimization criteria. These works seek to adequately determine the locations and capacities for the installations of flexible AC transmission systems (FACTS), and superconducting magnetic energy storage (SMES). Multi-objective programming approaches for static and dynamic (short-term) voltage stability improvement were developed in [19] and [2]. These approaches employed VCPI for quantifying the system voltage stability seeking the adequate placement of static synchronous compensators (STATCOMs) and multi-stage planning for aged SVC equipment retirement. More recently, new opportunities thanks to bulk power grid expansion/modernization are drawing significant attention and motivated important novel studies proposed within the literature. These works cash in of the many penetration of RESs and expansion of HVDC systems to enhance power systems voltage stability margin without the requirement of new compensators installation. In [20] the reactive power produced by grid-connected variable- speed wind generators was wont to enhance steady-state voltage stability margin. a replacement perspective considering both active and reactive power injections of photovoltaic systems was proposed in [21] to supply dynamic voltage support to short-term voltage stability. Additional control actions are developed in [22] to utilize VSC-HVDC for global enhancement of steady-state voltage stability. Although interesting and with meaningful results, the above- mentioned methods somewhat de- tract the first design of those systems and should not be of great appreciation in actual operative reality. Consequently, their applicability is restricted , as many operators would like to run these units at unity power factor, as long as active power production is that the one typically rewarded [23].These possible limitations are avoidable using power grid flexible resources capacity [5]. These resources can have their operation adapted to raised accommodate power grid requirements without compromising their core values design. Moreover, differently from the above-mentioned applications which will have their actions limited by the wants of the particular site at which the equipment are installed. Flexible resources are widespread within the network, allowing their use at the foremost effective locations to support various power grid operations and planning requirements [24–29].In [24] a replacement assessment of probabilistic flexibility is employed to avoid

RES power curtailment. Reference [25] presents the appliance of various emerging flexible re- sources as sources of scheduled energy reserve within the electricity market. Further, a replacement power grid expansion planning approach is proposed in [26] considering the participation of flexible resources aimed toward the reduction of latest assets acquisition. Moreover, flexible resources are especially important to voltage stability support as modern power grid move toward large integration of variable renewable resources, which may cause significant reductions within the system voltage stability margin and variations within the critical location liable for driving the system to voltage collapse. In [27] curtailable loads are considered as active market participants in heavily loaded systems seeking to make sure power grid voltage stability. The work developed in [28] proposes the appliance of DR to support voltage control actions, while considering the system voltage stability preservation. Next, the work proposed in [29] expands the attitude presented in [28], featuring optimal voltage regulation with DR participation for both primary and secondary control levels. Still, the present state-of-art falls short within the proposal of a way ready to take advantage of these distributed controllable resources to ensure secure voltage stability margins. this attitude is depicted in Table 1, presenting a comparison between available works within the literature and therefore the proposed approach.

3. Proposed Approach

Based on the main opportunities enabled by flexible resources and therefore the new voltage stability requirements of recent power systems, this paper proposes a completely unique area- based voltage stability index. The proposed index seeks to supply an immediate measure for flexible resources dispatch, with the target of guaranteeing reliable voltage stability margins for contemporary bulk power systems with significant penetration of RES generation. For this, the proposed approach consists of 4 main steps, respectively 1) voltage

To perform these steps, knowledge of the system current operating condition, i.e. loading, generation and system parameters, and forecasted direction of load increase are required. Using this information, first the system voltage stability margin is assessed employing the continuation method. supported this result, a system wide-sensitivity springs indicating the susceptibility of every bus to steer the system to voltage collapse. From this overall perspective, multiple coherence areas are determined and native area-based sensitivities obtained. This information is employed within the development of the proposed sensitivity index, providing an immediate multi-area perspective for flexible resources dispatch. To validate the proposed approach, comparative simulation case studies are administered in Matlab considering the IEEE 118-bus test system with modifications to reflect the progress of recent power systems toward large penetration of RESs and versatile resources. during this environment, the proposed approach is stressed with several case studies respectively divided in 1) Validation and performance evaluation, 2) Sensitivity analysis 3) Comparative analysis between flexible resources and RESs operation under voltage control for voltage stability support. These case studies showcase the necessity for voltage stability support in systems with significant penetration of RESs while depicting the superior ability of the proposed approach to make sure safe operative conditions. the benefits provided by the proposed approach as compared to the state-of-art are threefold and described as follows:

New outlook for voltage stability support of recent power grid supported flexible resources: the proposed area-based design enables the distributed potential of flexible resources to satisfy the sounding requirements of recent power systems voltage stability. Different from other approaches that might require new infrastructures or detract the first design of the prevailing explored system, as e.g

The numbers in Columns represents the fallowing terminology.

1= Static VAR compensation 2= VSC-HVDC

3= Load curtailment

4= RES

5= Flexible resources

6= Voltage control

7= Voltage stability

8= Secure voltage stability margin 9= RES curtailment reduction 10= Expansio planning

11= Schedule energy reserve

12= Direct system- wide solution method

Table 1.

HVDC, wind and solar-based applications [20-22], flexible resources are meant for this type requirement.

Prevention of early saturation in voltage stability margin improvement: The identification of critical cores and system partitioning allows the proposed index to work out the foremost effective buses for voltage stability support along different coherent areas of the network. This feature enables the system to avoid centralized actions during a single region, which just in case of a change within the critical location driving the system to voltage collapse would prevent local over-compensation and therefore the early saturation within the overall system load margin improvement.

Enhancement of bulk power grid voltage stability margin range: The proposed approach above- mentioned ability to stop early saturation allows for substantial increases in voltage stability support actions to be converted into continuous improvements within the system voltage stability margin. this is often a critical aspect for systems with broad participation of intermittent RESs which may not be achieved with system-wide based solutions, thanks to possible overcompensation during a specific region as large voltage stability support actions yield to changes within the most crucial location susceptible to voltage collpase.

4. Area-Based Voltage Stability

In this section the proposed area-based voltage stability support index is depicted. It presents the outline of a generic power grid with flexible resources, the procedure for the system voltage stability margin assessment, and therefore the respective process to derive the proposed area-based voltage stability support index.

4.1 Network Description

Consider a bulk AC transmission . The network consists of transmission lines with low r/x ratio, synchronous generation and RESs. The network nodes are contained within the set $N=G\cup £$, where G and £ respectively denote the sets of nodes with generation and loads, being possible that a node is contained in both sets, respectively $G\cap £=\emptyset$. The connection between two terminals i and j represented by $\upsilon: =\{i, j\}\subset N$. The set of transmission lines is denoted by $\upsilon: =\{i, j\}\subseteq N\times N$. Loads composition is denoted by a daily non-controllable portion and an aggregated flexibility parcel, respectively denoted by $k_i \in IR$ and $\varphi_i(flex) \in R$ FOR flex generic node i.

$P_i(L) = P_i L.(1- \varphi_i(flex)), 0 \leq \varphi_i(flex) < 1-K_i$ (1)

$P_i(L) = P_i(L)o [\alpha_i(P) \cdot \{| V_i \div V_iO|\}2+\beta_i(P) \{| V_i \div V_iO|\}+\gamma_i(P)$ (2)

where $\alpha_i(P) \in IR$ denotes the constant impedance (Z) share for a generic node i, constant current (I) and power (P) shares are defined by $\beta_i(P) \in IR$ being the participation coefficients subjected to the relation

$\{(\alpha_i+ \beta_i+ \gamma_i) = 1:[\alpha_i, \beta_i, \gamma_i] \in IRN3IRN=[0, 1]\} \ \forall \ i\subseteq £$

$V_i\in C$ denoted the phase voltage. The interested reader within the process of flexible resources aggregation is mentioned [30].

4.2 Flexible Resources

Power system flexibility represents the network capacity to capita- lize on the system available resources to reply to net demand change requests [31]. this attitude is out there through different power grid elements [32], out of which this work is concentrated on three main categories namely demand response, distributed generation, and electric vehicles. Demand response is that the ability of the system to manage its load through intentional curtailment, nominal supplied power adjustment or time-shifting of specific groups of interruptible loads thanks to operation requirements [28]. this attitude is following modeled for a generic node by the respective model depicted in [33],

$P_{i,DG}= \Sigma P a, \rho A_i = [p 1,\ldots\ldots p |A_i|]$ (3)

where P_i 〈DG〉 is that the total nodal i demand response capacity, A_i is about of interruptible/adjustable loads connected at node i, pa denotes the corresponding load demand for each load $A \in A_i$.

Following, distributed generation enables the injection of specific controllable contributions of power to the grid. These contributions are limited by their current dispatching power and respective rated gen- eration capacity [34].

$\{P_{i,DG:} \ P_i^{min}{}_{DG} \leq P_i \langle DG\rangle \leq P_i^{max}{}_{DG,}(P_{i_{DG}})^2+(Q_{i,DG})^2 \leq (S_i^{max}{}_{DG})^2\}$ (4)

Where Pi, 〈DG〉 and Qi, 〈DG〉 represent the unit current active and reactive power generation, P minDG, and P maxDG denote minimum and maximum active power generation, and S max denotes the DG rated power. In addition, equipment as EVs may perform both above-mentioned flexibility possibilities simultaneously [35-36]. These units may have their charging process interrupted or adjusted representing DR actions. also as, contributing with power injections during a similar way as a DG thanks to their ESS capacity. during this sense, these units flexibility is presented as an association of DR and DG.

$P_{i(EV)} = \sum P_i^k + P_i^k{}_{(DG)}, \{(P_i^k, P_i^k{}_{(DG)}):0\leq P_i^k \leq P_i^k \leq P_i^{k \text{ max charges}} 0 \leq P_i^k{}_{(DG)} \leq P_i^k \text{ max discharge}\}$ (5)

$K \in EV_i$

where P_i^k denotes the EV current charging power, P_i^k represents the EV reduction of charging power, i.e. DR, $P_i^k{}_{(DG)}$ is the power injection provided by the respective EV, i.e. DG. $P_i^{k \text{ max charges}}$, and P_i^k max discharge are the EV charger maximum charging and discharging power.

4.3 Voltage Stability Margin

Let each transmission node contained within the set be classified under one among the three operative modes: PV, PQ or Vθ, respectively composed in subsets PV , PQ and V . the facility system network are often represented by a generic nonlinear model:

$0 = f(x, \lambda)$ (6)

Where f: $IR^n \times IR \rightarrow IR^n$ may be a nonlinear function with space dimension $n = (|N_{PV}| + 2 \cdot |NPQ|)$, $| \cdot |$ is an operator that returns the cardinality of a generic set, $x := [\theta i, \dots \theta i_{|NPV|} + |NPQ|, Vi, \dots, V|NPQ|]^T \in IR^n$ $i \in N$ denotes the system state variables, $i \in IR$ represents a generic transmission node $\lambda \in IR$ a particular parameter that moves the system from one equilibrium point p0 to a different $p[\tau]$, where $\tau \in R$ represents the continuation iteration, and $0 \in IR^n$ represents a vector of all zeros. The system voltage stability are often studied by driving the system from a known initially stable operating condition up to instability. This instability condition is defined as bifurcation point and may be divided into two main category groups. the primary group represents instability conditions thanks to the merging of two equilibrium points resulting in a null eigen value, i.e. characterizing either a saddle-node (SNB), transcritical (TB) or pitchfork bifurcation (PB); or by the crossing of the imaginary axis by a pair of complex conjugate eigen values, representing a Hopf bifurcation (HP) [37]. The second group is said to power system operative limits, especially generators reactive power limits, being defined as limited induced bifurcations (LIB). this sort of bifurcation occurs thanks to violations in generators' limits, resulting in changes in these units operating mode from constant active power and voltage mode, i.e. PV mode, to constant active and reactive power mode, i.e. PQ mode, [38]. This action results in a replacement set of equations representing the respective power grid which will not be stable to the present operating condition, i.e. it's going to cause the merging of two equilibrium points with an abrupt crossing of eigen values from the right-half plane to the left-half plane side. It should be noted that the literature has consistently demonstrated that voltage collapse is especially connected to SNBs and LIBs [37-39]. during this perspective, a widely used approach within the literature to work out power system's voltage stability margin, i.e. the space between the present operating point to the purpose of voltage collapse, or SNB/LIB point, is predicated on the continuation method. This method is split into two steps: predictor and corrector. the primary step is liable for increasing the network load and generation supported a direction of load increase $[\lambda_{|T|} \in IR]$.This direction is assumed to be a known quantity, which may be a reasonable assumption provided adequate load forecast[39–40]. just in case that a reliable load forecast isn't available, a worst-case direction are often wont to make sure that the system presents a satisfactory distance to voltage collapse [41]. Procedures to the determine the worst-case direction are detailed depicted in [7–42].

$$P^{\ell}_{i,|\tau|} + J.Q^{\ell}_{i,|\tau|} = \left(P^{\ell}_{i,}{}^{(.)}|_{p0} + J.Q^{\ell}_{i,}|_{p0} \right).\lambda_{|\tau|}, \; C^{|NPV|+|NPQ|} \times IR \; C^{|NPV|+|NPQ|} \quad (7)$$

$$P^{g}_{i[\tau]} = P^{g}_{i}|_{po} \,.\, \lambda_{[\tau]}, : IR^{|NPV|} \times IR \rightarrow IR^{|NPV|} \quad (8)$$

where P^{ℓ}_{i}, $Q^{\ell}_{i,}$ and P^{g}_{i} denote the active and reactive power demands, and active power generation during a generic transmission node $i \in IR$. The second step could also be performed by solving the facility flow problem considering the predictor step because the initial guess. An efficient method to speed-up this problem solution is achieved by modeling $\lambda[\tau]$ as an adaptive parameter supported the tangent vector sensitivity [10].

where $Y[\tau]$ denotes the tangent vector sensitivity calculated in an equilibrium condition at a generic iteration τ, $Dx\, f|_{p[\tau]}$ is the Jacobian matrix $\rho \in IR$, may be a scalar gain wont to control the direction increase and $\partial f / \partial \lambda|_{p[\tau]}$ denotes the initially injected reactive and active powers. to scale back the expensive computational effort because the system approaches voltage collapse, stopping criteria are often included to terminate the continuation process. The stopping criteria denoted by ξ may be a voltage collapse index which will anticipate the vanishing eigen value, tending to zero because the bifurcation is approached. it's directly determined from (8) for a given operating point having a negligible calculation cost [43]. Reference [43] also addresses that employing the CRIC method can reduce computational burden, turning the continuation method eligible for load margins calculation.

$$\xi = ||Y_{[\tau]}||^{T}.\, Dx f|_{p[\tau]}.||Y_{[\tau]}|| \quad (11)$$

4.4 Proposed Area-Base Voltage Stability Support

Based on the voltage collapse information the proposed area-based sensitivity index is developed. For this sake, a completely unique methodology composed of three main stages is proposed: 1) system-wide perspective for the definition of most crucial buses; 2) area-based sensitivity providing the characterization of critical cores and coherence areas; and 3) area-based voltage stability index responsible to work out the foremost effective buses and their respective contribution for voltage stability support. First, a system-wide sensitivity is obtained indicating the susceptibility of each bus to steer the system to voltage collapse. This sensitivity is achieved through the calculation of the tangent vector at the vicinity of the voltage collapse point denoted by Y#: = dx/dλ $|_{p\to p\#}$; reference on his voltage stability technique is out there in [10]. supported this information, the PQ-buses criticality indexed by YPQ # are extracted from the complete set Y#, and a ranking is performed to spot the foremost and least effective buses for voltage stability support, respectively denoted by the

set B^{+} : $=\{\beta 1^{+},\ldots,\beta_{\Omega}\}\subseteq N_{PQ}$

$$Y_{\#} =: [Y_{\#}^{PV}, Y_{\#}^{PQ}]^{T} \quad (12)$$

$$Y_{\#}^{PQ} = [Y_{1}{}^{\theta}{}_{\#},\ldots\ldots Y^{\theta}{}_{|N(PQ)|,\#}, Y_{1}{}^{V}{}_{,\#},\ldots\ldots Y^{V}{}_{|N(PQ)|,\#,}]^{T} \quad (13)$$

$$Y_{\downarrow}{}^{PQ}{}_{\#}: \mathrm{rank}_{\downarrow}(\mathrm{abs}(Y_{\#}{}^{PQ})) \quad (14)$$

$$Y_{\downarrow}{}^{PQ}{}_{\#} =: [Y_{\downarrow}{}^{PQ}{}_{1},\ldots\ldots Y_{\downarrow}{}^{PQ}{}_{2|N(PQ)|}]^{T} \quad (15)$$

$$B^{+} = \{(\beta^{+}{}_{n}): \beta^{+}{}_{n} = \beta_{i}{}^{PQ}|Y_{i}{}^{PQ}{}_{n} = Y_{i}{}^{PQ}{}_{n,}\ i\in N[1, 2.]|N_{PQ}|],\ n\in N[1,\Omega] \quad (16)$$

where rank↓(·) may be a function that returns the descending rank of a generic vector, $Y_{\downarrow}{}^{PQ}{}_{\#}$ is that the ranked criticality index, $\beta_{i}{}^{PQ}$ corresponds to the buses that structure $Y_{\#}{}^{PQ}$, and $\beta^{+}{}_{n}$ denotes the ranked buses. From this process, the buses classified because the best for voltage stability support are typically contained within the same neighborhood of the node liable for driving the system to voltage collapse, resulting in a concentrated actuation. However, bulk power systems usually contain quite one coherence area; i.e., a neighborhood of the

system comprising buses with similar behavior, here denoted by the sets $Z_{m}\subseteq N$, where m∈ [1, ℧] indicates the world index and ℧ denotes the entire number of areas. during this sense, bearing in mind that the voltage collapse may be a local phenomenon, the characterization of the buses sensibility from a system-wide perspective in bulk power systems environments wouldn't render the expected effect, because the centralized action within the system most crucial region, Z_1, wouldn't produce meaningful improvements in other coherence regions, i.e. P-Vɵ ← $Z_{m}{}^{+}$ ≈ P-Vɵ ← Z_{m} ∀ m≠1

where P-Vɵ ← Z_{m} are representations of the system voltage stability when each respective coherence area Z_{m} assumes the condition to drive the system to voltage collapse; superscript + denotes the system response after system-wide based compensation. to get P-Vɵ ← Z_{m} m just in case that the world under analysis isn't the foremost critical region originally leading the system to voltage collapse, i.e. Z_{m}|m≠1, compensations are performed within the more critical region(s) until the voltage collapse condition is shifted to the region Z_{m} of interest. during this perspective, system-wide based approaches would fail just in case that a big improvement within the system load margin is required. the belief of an outsized compensation would render a considerable increase within the voltage stability margin of the critical region, P-Vɵ ← $Z_{1}{}^{+}$. However, under a system perspective, this action would only move the start line of voltage collapse to the next most crucial region, Z_{m}| m≠1, which has not been improved by this compensation. This results in an early saturation within the actual improvement capacity of the system voltage stability by the next most critical area voltage collapse condition, i.e P-Vɵ ←ɵ$^{+}$ = P-Vɵ ← $Z_{2}{}^{+}$| P-Vɵ ← $Z_{2}{}^{+}$≈ P-Vɵ ← Z_{2} ,

Where P-Vɵ ←ɵ$^{+}$ depicts the particular system P-V curve after system-wide compensation. As a result, the system would presumably not be ready to achieve the specified load margin improvement, ζ, where the respective lacking margin is denoted by χ. This condition is clearly depicted in Fig. 1. It shows the voltage stability profile of a bulk power grid with several coherence areas before and after the system-wide compensation. Where symbol S op denotes the system operating point, and ε% is that the required secure margin between the operative point and therefore the point of voltage collapse. This value is established by specific regulations as [1].

Figure 1.(P-V curve for wide approach system)

In this perspective, the event of voltage stability support strategies supported system-wide approaches may not be efficient to make sure safe operating conditions, as power systems move toward me voltage stability requirements thanks to the increasing penetration of RESs. This new perspective requires a big capacity for voltage stability margin improvement and skill to effectively tackle constant shifts within the start line of voltage collapse across different regions of the system. Seeking to accomplish these challenges and avoid the previously mentioned limitations, a second stage is developed supported the previous system-wide sensitivity. The proposed approach identifies local critical cores for voltage collapse and divide the system into coherence areas denoted by the sets $Z_m \subseteq \mathcal{N}$. the utilization of coherence areas is proven as an efficient solution to enhance voltage related actions thanks to these phenomena local characteristics, e.g. disturbance propagation and security regions applications [44-45], however the proposed perspective and application haven't yet been explored. The definition of critical cores avoids the centralized compensation performed by the system-wide approach, allowing a greater range for the system voltage stability margin improvement, ζ. Moreover, as compensation becomes distributed throughout the network, it's possible to repeatedly tackle the event of voltage collapse even when a change within the region conducive to the present incidence is imposed. This feature is clearly shown in Fig. 2. The proposed area-based strategy can improve all coherence areas voltage stability margin, i.e. $\text{P-V}\theta \leftarrow Z^{++}{}_m \neq \text{P-V}\theta \leftarrow Z_m \; \forall \; m \in \mathcal{N} [1, \mho]$.

Therefore, allowing the achievement of the required/desired voltage stability margin improvement, $\zeta \in \mathrm{IR} | \chi = 0$, even for scenarios demanding large improvements within the system loading margin. The system responses after the proposed area-based voltage stability support are denoted by the superscript++ respectively $\text{P-V}\theta \leftarrow \theta^{++}$ and $\text{P-V}\theta \leftarrow Z^{++}{}_m \forall \; m \in \mathcal{N} [1, \mho]$.

Figure.2 (P-V Curve for area base approach)

The initial step to divide the system into coherence areas is that the definition of the primary critical core, $\beta_1{}^{++}$, which is given by the system's most crucial PQ-bus, i.e. $\beta_1{}^{++} = \beta_1{}^{+}$. Following, supported the foremost critical location the neighbor buses belonging to an equivalent area, m, are determined. For this, a scanning process is performed where the association of a candidate bus i is completed if its normalized criticality index is bigger than the partition parameter denoted by , i.e. $\phi \in \mathrm{IR}$ i.e $(Y_{i,\#}/Y^{++})$ and therefore there exists an electrical connection 2 between the candidate bus and the previously associated buses contained within the same area. Discussions about the determination of the partitioning parameter are omitted thanks to space constraints, the reader is mentioned [10] where a comprehensive analysis is developed indicating that φ should be set within the range of 0.5 to 0.75. This process is performed for about the Vθ bus, V , which is manually related to the respective coherency area at the top of the method . Next, the respective buses collected in m are extracted from the set of obtainable buses for network partitioning and therefore the process repeated. After completing the primary area division, subsequent critical core, m ‡ , is decided because the best PQ-bus that's not contained within the previous area(s) division then on. This procedure is repeated until each bus is allocated during a respective area. the method that identifies the coherence areas $\{ Z_m, \forall m \in N[1, \mho]\}$ around their respective critical cores $\{\beta_m^{++} \forall m \in N[1, \mho]\}$ is described as follows:

$$Y_m^{PQ}{}_{\#,}: [Y^{\theta}{}_{i\#,} \ldots Y^{\theta}{}_{|Nm^{PQ}|,\#}, Y^{V}{}_{i,\#} \ldots\ldots Y^{V}{}_{|Nm^{PQ}|,\#}]^{T} \forall i \in N_m^{PQ} \quad (17)$$

$$Y^{++}{}_{m\#,}: \max(\mathrm{abs}(Y_m^{PQ}{}_{\#,})) \quad (18)$$

$$Z_m = \{(\beta^{++}{}_m): \beta^{++}{}_m = \beta_i^{PQ} | Y_i^{PQ}{}_{m,\#} = Y^{++}{}_m \; i \in N[1, 2.]|N_{PQ}\} \quad (19)$$

$$Z_m = \{(\beta_i): Y_{i,\#}/Y^{++}{}_{m,\#} > \phi, i \in \upsilon | z_m, i \in N[1, n] \quad (20)$$

$$N_{m+1} = N_m Z_m \quad (21)$$

$$N^{PQ}{}_{m+1} = N^{PQ} N_{m+1} \quad (22)$$

where N_m, $N^{PQ}{}_m$ and $Y_m^{PQ}{}_{\#}$ respectively denote the sets of all buses, PQ buses and criticality index of flexible PQ-buses that aren't associated to any area. $Y^{++}{}_{m,\#}$ represents the criticality index of the critical core $\beta^{++}{}_m$. Z_m represents the buses collected during a respective coherence area $m \in$ IR, while β_i denotes the bus like the criticality index $Y_{i,\#}$. The initial conditions are given by $Z = \emptyset$, $N_1 = N$, $N_1^{PQ} = N^{PQ}$. The respective set collecting all critical cores is defined by

$B^{++} = \{\beta_1^{++}, \ldots, \beta_{\mho}^{++}\} \subseteq N^{PQ}$. By using the critical cores and coherence areas knowledge, a completely unique area-based voltage stability index is obtained for every bus. This index, denoted by Ψ_i, ∇, consists of two terms. the primary term represents the area's contribution supported the density of critical spots, while the second term denotes the respective contribution from the bus supported its criticality information. this suggests that if one area features a very critical location susceptible to voltage collapse but possesses a coffee density of critical buses, the entire compensation during this area won't be performed in excess, as compensating this very critical spot renders an overall improvement of the area's voltage stability. On the contrary, if a neighborhood features a high density of critical points, additional compensation are going to be required, because the compensation of the only most crucial location won't cause an actual improvement of the world voltage stability profile. The proposed index $\Psi_i^{++}{}_{(\nabla)}$, and therefore the flexibility contribution of every bus, denoted by the set $\Psi_{(\nabla)}$, are represented by the subsequent equations

$$Y_{m,(v)} = \{(Y_{i(v)}): Y_{i(v)} = Y_{i,\#}/Y^{++}{}_{m,} \; \beta_i \in Z_m, \; i \in N[1, \Gamma_m], m \in N[1, \mho]\} \quad (23)$$

Figure: 3. (Proposed Methodology)

$\Psi^{++}{}_{\mathfrak{M},(\nabla)} = \{(\Psi_i{}^{++}{}_{,(\nabla)}): \Psi_i{}^{++}{}_{,(\nabla)} = (||\boldsymbol{\gamma}\mathfrak{M}_{,(v)}|| \,.\, \boldsymbol{\gamma}_i, \nabla/M=1\mho||\gamma M, v\ I=1\Gamma M\gamma i(v))$

$Y_{i,(v)} \in Y_{\mathfrak{M},(v),}\ i \in N[1, \Gamma_{\mathfrak{M}}], \mathfrak{M} \in N[1, \mho]\}$ (24)

$\Psi_{(V)} := \{\Psi^{++}{}_{m(v)}. \Lambda, \ldots\ldots \Psi^{++}{}_{\mho;(v)}.\Lambda\}, m \in N[1, \mho]$ (25)

Where $Y_{i,(v)}$ represents the criticality of generic bus m∈IR, Γm is that the number of buses used for compensation in area m∈IR, $Y_{\mathfrak{M},(v)}$ and $\Psi^{++}{}_{\mathfrak{M},(\nabla)}$ are sets containing the buses criticality and proposed index of a respective area m∈IR, and Λ represents the entire system flexibility usage, i.e. $\sum_{i\in\lambda} P_{i(DR)} + P_{i(DG)} + P_{i(EV)} = \Lambda$. The depth description of the method to get the proposed area based voltage stability index is illustrated in Fig. 3.32.

5 Result and Discussions

This section depicts the need for area-based voltage stability support as power systems move toward large penetration of RESs. Here comparative case studies are developed to showcase the improvements provided by the proposed approach for contemporary power systems' voltage stability support, in contrast to traditional direct system-wide strategies and successive applied mathematics (SLP).

106	108	101	79	78	118	43	35	37

Table. 2 (RESs Placement or allocation)

For this purpose, case studies are developed employing the IEEE 118-bus system modified to represent grid developments, where power systems are likely to experience operating conditions on the brink of their limits with a rise in RESs penetration. The system load is doubled as compared with the bottom case,and a complete of 20 p.u. of additional wind power are evenly distributed on buses as described in Table 2. during this analysis, a conservative case study is used . Loads are modeled as constant power in order that voltage reductions wouldn't improve the system voltage stability capacity, and a unity power factor is assumed for flexible resources such the reactive power consumption is maintained at nominal level. during this configuration, the system operates with a voltage stability margin of 108% surpassing the Western Electricity Coordinating Council (WECC) minimum requirement of 105% [1]. during this standard, the present system operative condition denoted by S op represents the system loading margin at 100%. the need for a further 5% stability margin, ε = 5%, is an industrial standard that seeks to accommodate possible unpredicted load variations adopted by several system operators worldwide. due to RESs lack of guaranteed power contribution, scenarios with low generation states can meaningfully affect the system voltage stability margin and even lead the system to operating conditions beyond the voltage stability limit. This scenario requires effective voltage support actions to make sure a reliable system operation, which is explored by the performed case studies considering flexible resources usage to ensuresecure voltage stability margins within the absence of RESs contribution. during this perspective, three main case studies are developed to demonstrate the proposed approach effectiveness: 1) Validation and performance evaluation; 2) Sensitivity analysis; and 3) Comparative analysis between flexible resources and RESs operating under voltage

control for voltage stability support.

5.1 Performance Evaluation and Validation

The first case study highlights modern power systems significant need for voltage stability support and therefore the superior ability of the proposed area-based approach to affect the new system operative reality and requirements. For this, comparisons with a standard direct system-wide approach and SLP [46] are performed. The comparative system-wide approach is predicated on the sensitivity of the tangent vector.

This technique was proposed in [10] and employed in [3] to work out the set of candidate buses for voltage stability support. For this, four sub-cases are developed, respectively: Case 1 - System behavior without voltage stability support; Case 2 - System behavior with flexible resources supported traditional direct system-wide strategy; Case 3- System behavior with flexible resources support supported the proposed direct area-based voltage stability index; Case 4 - System behavior with flexible resources support supported successive applied mathematics . The respective voltage stability profile of the system for Cases 1–3 are depicted in Fig. 4(a)-(b) where P-Vɵ ← ɵ depicts the particular system P-V curve, P-Vɵ ← z_m are representations of the system voltage stability when each respective coherence area z_m assume the condition to drive the system to voltage collapse. The system responses without voltage stability support (Case 1) are denoted by the representations without superscript, while the system behavior after the supply of voltage stability support supported system-wide (Case 2) and therefore the proposed area-based approach (Case 3) are respectively denoted by the superscripts + and ++, $op_{ɞ}$ indicates the system operating condition, ζ describes the required improvement within the system loading margin and χ represents the residual voltage stability margin to make sure the system operation within the established limits by regulation. during this system, nine buses are used for flexible resource support and three coherence areas are defined. Fig. 4(a) depicts the system behavior for Cases 1–2. supported this figure one can conclude about the system requirement for voltage stability support, changes within the critical region that lead the system to voltage collapse and therefore the consequent inability of the system-wide approach to realize large improvements within the system load margin. Analyzing Fig. 4(a), one may observe that the foremost critical region P-V curve for Case 1, i.e. when the dispatchable generators provide the network's expected RES generation and no action is taken to enhance the system voltage stability margin, P-Vɞ ← z_1 represents the particular overall system voltage stability margin, P-Vɞ ← ɞ = P-Vɞ ← z_1. during this scenario, although the power/demand balance are often achieved, the system would experience voltage collapse, because the system loading margin denoted by S S = 0.98 | P-Vɞ ← ɞ , is less than the particular demand requirement, $op_{ɞ}$ = 1.00. during this sense, actions must be taken to enhance the system voltage stability to make sure the specified secure operating condition of $\boldsymbol{\lambda}$ = 1.05. to realize this goal, an improvement of seven within the system load margin is important , i.e .ζ = 7%. during this sense, first, flexible resources are wont to provide voltage stability support supported a system-wide perspective. together may observe, the system-wide strategy can significantly enhance the voltage stability margin of the originally most crucial region of the system to $\boldsymbol{\lambda}$ = 1.11 |P-Vɞ ← z_1^{+}, however, this improvement wasn't translated to the general system stability margin expressed by P-Vɞ ← $ɞ^{+}$. The centralized actuation within the most crucial buses isn't ready to improve other regions voltage stability, P-Vɞ ← Z_m^{+}= P-Vɞ ←$z_{m,}$ ∀ m≠1| m∈N [1, 3]. In contrast, it results in the overcompensation of the previously most crucial region of the system, Z_1, resulting in the change of the situation responsible to drive the system to voltage collapse to subsequent most crucial region, i.e. Z_2. Therefore, limiting the system voltage stability margin improvement by the next most crucial area voltage collapse condition, P-Vɞ ← $ɞ^{+}$=P-Vɞ ← Z_2^{+}, which didn't have its load margin significantly suffering from the performed compensation, i.e. P-Vɞ ← Z_2^{+}≈ P-Vɞ ← Z_2. During this perspective, the system improved stability margin after voltage stability support supported system-wide perspective is denoted by $\boldsymbol{\lambda}$ = 1.01 |P-Vɞ ← $ɞ^{+}$. The obtained condition remains less than the WECC safe operating margin criteria of 105%, remaining 4% of the specified voltage stability margin to be fulfilled, i.e. χ = 4%. This result would inevitably demand costly system expansions and installation of latest infrastructures to succeed in the regulation criteria [1]. Seeking to satisfy the secure voltage stability margin requirement and avoid costly system upgrades, the proposed area-based voltage stability index is used , being the results depicted in Fig. 4(b). From Fig. 4(b) one can observe that the flexible resources usage supported the proposed area-based approach results in an overall improvement within the system voltage stability margin. during this scenario, all system coherence areas have achieved the voltage stability margin requirement by WECC, i.e. $\boldsymbol{\lambda}$≥1.05|P-Vɞ ← Z_m^{++} ∀ m∈N [1, 3]. As well, after performed the proposed area-based voltage stability support, the system most crucial region was shifted to the coherence area Z_3, P-Vɞ ← $ɞ^{++}$= P-Vɞ ← Z_3^{++}. However, differently from the system-wide strategy, the proposed approach distributed action within the network critical cores can satisfactorily address this issue, overcoming the first saturation faced by the system-wide strategies and resulting in a system voltage stability margin of $\boldsymbol{\lambda}$ = 1.05 |P-Vɞ ← $ɞ^{++}$=. The obtained results are thanks to the distributed actions within the network most crucial cores, which allows for a greater range of improvement to the system voltage stability margin, ensuring the specified load margin improvement of ζ= 7%|χ = 0 with a flexibility usage of Λ = 2.5 p.u.. Following, a replacement case study is developed seeking to verify the proposed direct approach ability to work out the system most adequate allocation for flexible resources support as compared with SLP.

Figure 4(a) (before and after curve for system voltage stability based on system wide strategy)

Figure 4(b) (before and after curve for system voltage stability based on proposed area based index)

The obtained results present significant similarity between the proposed direct approach and SLP, i.e. 67% of the chosen buses for flexible resources usage are common for both methods. Moreover, an equivalent level of voltage stability margin improvement is achieve by both methods using the same amount of flexibility, i.e. λ = 1.05 for both Case 3 and Case 4 with a flexibility usage of Λ = 2.5 p.u..These results showcase the proposed direct approach ability to meaningfully improve the system load margin at a significantly reduced computational cost. Eliminating the computational burn imposed by the successive iterations necessary for gathering feedback information required by optimization technics. A summary of the system voltage stability margin for Cases 1–4 is presented in Table 3. The respectively selected buses and their flexibility usage for Cases 2–4 are shown in Table 4, where the entering of all buses' flexibility usage for every case study in Table 4 must be adequate to the total amount of flexibility usage defined by Λ.

5.2 Analysis for Sensitivity

In this section sensitivity analyses are performed to research the influence of loads uncertainty and versatile resources usage impact on the system voltage stability margin. The performed case studies present global system sensitivities, seeking to spotlight the proposed method capability to satisfy secure voltage stability margins, prevent early saturation and significantly improve the system voltage stability margin range. First, the impact of load uncertainty is addressed featuring load scenarios extracted from [28]. These case-studies denoted as S1, S2, and S3 represent the system loading for 98%, 100% and 102%, respectively. Obtained results indicate that the proposed approach is in a position to satisfactorily address loads uncertainty without prejudice to the guarantee of secure voltage stability margin. altogether analyzed case studies, the required range of improvement is met, i.e. there's no remaining voltage stability margin to be fulfilled, χ = 0%. the pliability usage for every scenario are respectively, S1: ζ; = 5%| = 1.5 p. u; S2: ζ= 5%| = 2.5 p. u; and S3: ζ= 5%| = 4.0 p. u.. an in depth description of every bus contribution is presented in Table

Figure. 5 (sensitivity of voltage stability margin using different flexibility usage level)

Next, the sensitivity of voltage stability margin with reference to flexible resources usage are investigated and illustrated in Fig. 5. For this, a technique almost like the one presented in [29] is employed, during which successive variations within the use of flexibility are performed and therefore the voltage stability margin of the system is analyzed. together may observe, the proposed approach sustains significant improvements within the system voltage stability margin with the increasing usage of flexibility. Moreover, an outsized improvement within the operational range is verified. This results is predicted given the proposed area-based index distributed action within the network critical cores. during this perspective, all system coherence areas are compensated considering the criticality of the respective region, therefore avoiding the overcompensation during a single region and therefore the consequent inefficiency within the overall improvement of system voltage stability margin. For comparison sake, a standard system-wide approach is presented, where one can observe a rapidly saturation with a flexibility usage of Λ= 0.4 thanks to its centralized compensation within the most crucial nodes. additionally , it should be noted that local voltage stability sensitivity metrics are embedded within the proposed approach to define the respective candidate buses. during this sense, the chosen buses for flexible resource usage depicted in Table 4, represent the system most locally sensible buses under voltage stability perspective.

5.3 RES Operating under voltage Control and Flexible Resources

mathsize="6pt"This section seeks to assess flexible resources ability to enhance voltage stability as compared , and in association, with RES generation under voltage control. Different flexible resources are considered, including dispatchable DGs of rated power {15,8,10,14}MVA connected in buses {109,108,41,33}; EVs with level 2 chargers presenting charging/discharging capacity of 11 kW associated within the respective amounts, i.e. number of EVs, {250, 250, 380; 330, 460, 290, 150, 240, 190} at selected buses for flexibility support, i.e. buses {109, 108, 106, 41, 39, 44 33, 35 117}; also as DR capacity as necessary. The dispatch of flexible resources is predicated on priority rank seeking to maximise demand supplying, i.e. DGs are the primary to be used, followed by EVs, and just in case that additional flexibility is important DR is applied. Given the paper goal of improving power systems voltage stability, renewables operating under voltage control have their reactive power focused on load margin enhancement [47], i.e. $f = \boldsymbol{\lambda} - C_V \cdot [\sum_{\forall i} \max(0, |V_i| - V^{max}) + \sum_{\forall i} \max(0, |V_i| - V^{min})]$ where each unit has the subsequent local setting $Q_i = Constr(\hat{Q}_i + \alpha \Delta P_i, Simax2 - (\hat{P}_i + \Delta P_i))|V_i \leq V^{max}$ $Constr(x, x^{max}) = \{x, |x| \leq x^{max}; (x/|x|) \cdot x^{max}$, otherwise$\}$ where f denotes the target function, Cv is that the penalty term for voltage violation, V^{max} and V^{min} denote the utmost and minimum operational voltage limits, S_i^{max} is that the unit rated power capacity, α_i is that the slope coefficient and $\hat{Q}_i$ and $\hat{P}_i$ are reactive and active power set points. Here three comparative case studies are presented: 1) RESs operating under voltage control, ɞ^*; 2) Sole use of flexible resources, ɞ^{++}; 3) Combined use of flexible resources and RESs operating under voltage control, ɞ^{*++}. The respective results are depicted in Fig. 6. together may observe, RESs operation under voltage control are able to improve the system load margin up to 103% employing a combined total of 8.3 p.u.. Still, their contribution isn't sufficient for ensuring the required secure load margin established by WECC regulation, i.e. 105%. this attitude is significantly enhanced considering the utilization of flexible resources. As depicted by P-V← ɞ^{++} in Fig. 6, with an equivalent 8.3 p.u. of flexible resources usage, one are able to do a system voltage stability margin of 110%. This result significantly surpass WECC operational requirements and represents an improvement of 42% in comparison with RESs support. Demonstrating that flexible resources are simpler than RESs operating under voltage control to enhance the system voltage stability. These results are expected as flexible resources dispatch are performed from the system most crucial nodes under voltage stability perspective, whereas RESs contribution are conditioned to the situation of the unit installation. These locations are typically subjected to the supply of potential capacity for the respective development, e.g. wind generators, and should not be the foremost adequate location for voltage stability support. Still, a operation of RESs under voltage control and flexible resources can significantly improve the system voltage stability and cause a more efficient use of flexible resources. during this case, RESs action take priority over flexible resources, which are wont to fulfill the remaining gap to make sure secure voltage stability margins. This operation results in meaningful benefits as flexible resources usage is significantly reduced. A comparison with Case 2 in Section 4.1 indicates that by combining the utilization of flexible resources and RESs under voltage control, a discount of 56% within the total application of flexible resources is achieved. Moreover, this reduction represents a decrease of 73% in DR usage when considering multiple sources of flexibility, which can significantly avoid possible curtailments requirements. The detailed load margin is illustrated by P-V← ɞ^{++} in Fig. 6, while the contribution of every group is depicted in Table 6.

Figure 6. (Comparative analysis of flexible resources and voltage stability margin considering renewable operation under voltage control)

6. Conclusion

Traditional methods may not be efficient for securing safe voltage stability margin for power systems moving toward large penetration of intermittent RESs. during this paper, a completely unique area-based outlook using flexible resources is proposed to tackle this new power grid perspective. The proposed approach can overcome the first saturation within the improvement of power grid voltage stability margin faced by traditional centralized strategies which will endanger the achievement of secure operative conditions for contemporary power systems. For this, the system most crucial cores and their respective coherence areas are identified. supported this information a completely unique distributed voltage stability index is developed. The results indicate that the appliance of the proposed index to spot effective buses for voltage support and their respective ability of accelerating the system load margin, in association with flexible resources, is in a position to greatly improve and secure safe static voltage stability margins. the most contributions of this work are often summarized as follows:

• Proposal of a completely unique area-based voltage stability index considering bulk power grid coherence areas and important cores;

• Development of a replacement outlook for voltage stability support of modern power grid supported flexible resources;

• Prevention of early saturation in improving the general system voltage stability margin thanks to centralized overcompensating;

• Significant enhancement of bulk power grid voltage stability margin range, a critical condition for an influence system with large penetration of intermittent RESs generation.

7. References

[1] Reactive Reserve Working Group (RRWG), "Guide to WECC/NERC planning standards I.D: Voltage support and reactive power," Western Electricity Coordinating Council, Mar. 2006.

[2] J. Liu, Y. Xu, Z.Y. Dong, K.P. Wong, Retirement-driven dynamic VAR planning for voltage stability enhancement of power systems with high-level wind power, IEEE Trans. Power Syst 33 (2) (2018) 2282–2291.

[3] A.C. Zambroni de Souza, L.M. Honório, G. L. Torres, Increasing the loadability of power systems through optimal-local-control actions, IEEE Trans. Power Syst. 19 (1) (2004) 188–194.

[4] M. Bakhtvar, A. Keane, Allocation of wind capacity subject to long term voltage stability constraints, IEEE Trans. Power Syst 31 (3) (2016) 2404–2414.

[5] J. Kazempour, B.F. Hobbs, Value of flexible resources, virtual bidding, and selfscheduling in two-settlement electricity markets with wind generation-Part I: principles and competitive model, IEEE Trans. Power Syst 33 (1) (2018) 749–759.

[6] H. M.-Rad, Optimal demand bidding for time-shiftable loads, IEEE Trans. Power Syst 30 (2) (2014) 939–951.

[7] T. Van Cutsem, C. Vournas, Voltage Stability of Electric Power Systems, Springer, Boston, 1998.

[8] P. Kessel, H. Glavitsch, Estimating the voltage stability of a power system, IEEE Trans. Power De 1 (3) (1986) 346–354.

[9] P. Sauer, M.A. Pai, Power system steady-state stability and the load-flow Jacobian, IEEE Trans. Power Syst. 5 (4) (1990) 1374–1383.

[10] A.C. Zambroni de Souza, C.A. Cañizares, V.H. Quintana, New techniques to speed up voltage collapse computations using tangent vectors, IEEE Trans. Power Syst 12 (3) (1997) 1380–1387.

[11] M. Moghavvemi, O. Faruque, Real-time contingency evaluation and ranking technique, IEEE Proc. Gener. Transm.Distrib. 145 (5) (1998) 517–524.

[12] W.P.J. Philippe, S. Eftekharnejad, P.K. Ghosh, Development of a new voltage stability index and its implementation considering voltage, measurement uncertainty, IET Gener. Transm.Distrib 13 (18) (2019) 4011–4020.

[13] M. Kamel, A.A. Karrar, A.H. Eltom, Development and application of a new voltage stability index for on-line monitoring and shedding, IEEE Trans. Power Syst 33 (2) (2018) 1231–1241.

[14] Z. Liu, A. Clark, P. Lee, L. Bushnell, D. Kirschen, R. Poovendran, Submodular optimization for voltage control, IEEE Trans. Power Syst 33 (1) (2018) 502–513.

[15] S.C. Chevalier, P.D. Hines, Mitigating the risk of voltage collapse using statistical measures from PMU data, IEEE Trans. Power Syst 34 (1) (2019) 120–128.

[16] C.A. Cañizares, Z.T. Faur, Analysis of SVC and TCSC controllers in voltage collapse, IEEE Trans. Power Syst 14 (1) (1999) 158–165.

[17] S. Gerbex, R. Cherkaoui, A.J. Germond, Optimal location of multi-type FACTS devices in a power system by means of genetic algorithms, IEEE Trans. Power Syst 16 (3) (2001) 537–544.

[18] X. Huang, G. Zhang, L. Xiao, Optimal location of SMES for improving power system voltage stability, IEEE Trans. Appl. Supercond 20 (3) (2010) 1316–1319.

[19] Y. Xu, Z.Y. Dong, C. Xiao, R. Zhang, K.P. Wong, Optimal placement of static compensators for multi-objective voltage stability enhancement of power systems, IET Gener. Transm.Distrib 9 (15) (2015) 2144–2151.

[20] V.S. Kumar, K.K. Reddy, D. Thukaram, Coordination of reactive power in gridconnected wind farms for voltage stability enhancement, IEEE Trans. Power Syst 29 (5) (2014) 2381–2390.

[21] K. Kawabe, Y. Ota, A. Yokoyama, K. Tanaka, Novel dynamic voltage support capability of photovoltaic systems for improvement of short-term voltage stability in power systems, IEEE Trans. Power Syst 32 (3) (2017) 1796–1804.

[22] O.A. Urquidez, L. Xie, Singular value sensitivity based optimal control of embedded VSC-HVDC for steady-state voltage stability enhancement, IEEE Trans. Power Syst 31 (1) (2016) 216–225.

[23] M. Kayikci, J.V. Milanovic, Reactive power control strategies for DFIG-based plants, IEEE Trans. Ener. Conv 22 (2) (2007) 389–396. [24] Z. Lu, H. Li, Y. Qiao, Probabilistic flexibility evaluation for power system planning considering its association with renewable power curtailment, IEEE Trans. Power Syst 33 (3) (2018) 3285–3295.

[25] E. H.-Forushani, M.E.H. Golshan, M. S.-khah, P. Siano, Optimal operation of emerging flexible resources considering sub-hourly flexible ramp product, IEEE Trans. Sustain. Ener 9 (2) (2018) 916–929.

[26] H. Hamidpour, J. Aghaei, S. Pirouzi, S. Dehghan, T. Niknam, Flexible, reliable, and renewable power system resource expansion planning considering energy storage systems and demand response programs, IET Renew. Power Gener. 13 (11) (2019) 1862–1872.

[27] A. Jalali, M.S. Sepasian, M.K.S.-E. Eslami, Undisruptive load curtailment scheme to ensure voltage stability margin, IET Gener.Transm.Distrib 13 (9) (2019) 1509–1519.

[28] A. Rabiee, A. Soroudi, B. M.-ivatloo, M. Parniani, Corrective voltage control scheme considering demand response and stochastic wind power, IEEE Trans. Power Syst.

29 (6) (2014) 2965–2973.

[29] A. Rabiee, S.M. M.-Bonab, M. Parniani, I. Kamwa, Optimal cost of voltage security control using voltage dependent load models in presence of demand response, IEEE

Trans. Smart Grid 10 (3) (2019) 2383–2395.

[30] B.P. Bhattarai, I.C. Mendaza, K.S. Myers, B. B.-Jensen, S. Paudyal, Optimum aggregation and control of spatially distributed flexible resources in smart grid, IEEE Trans. Smart Grid 9 (5) (2018) 5311–5322.

[31] A. Akrami, M. Doostizadeh, F. Aminifar, Power system flexibility: an overview of emergence to evolution, J. Mod. Power Syst. Clean Energy 7 (5) (2019) 987–1007.

[32] IEA-PVPS Task 14, Flexible resources for flexible transmission system operation, Int. Ener. Agency Photovoltaic Power Syst. Programme (2017) Milan, October.

[33] A. M.-Rad, V.W.S. Wong, J. Jatskevich, R. Schober, A. L.-Garcia, Autonomous demand- side management based on game-theoretic energy consumption scheduling for the future smart grid, IEEE Trans. Smart Grid 1 (3) (2010) 320–331.

[34] E. Lannoye, D. Flynn, M. O'Malley, Evaluation of power system flexibility, IEEE Trans. Power Syst 27 (2) (2012) 922–931.

[35] P. Palensky, E. Widl, M. Stifter, A. Elsheikh, Modeling intelligent energy systems: co-simulation platform for validating flexible-demand EV charging management, IEEE Trans. Smart Grid 4 (4) (2013) 1939–1947.

[36] Y.R. Rodrigues, A.C. Zambroni de Souza, P.F. Ribeiro, An inclusive methodology for plug-in electrical vehicle operation with G2V and V2G in smart microgrid environments, Int. J. of Electric Power &Ener. Syst 102 (2018) 312–323.

[37] W. Rosehart, C.A. Canizares, V.H. Quintana, Effect of detailed power system models in traditional and voltage stability constrained optimal power flow problems, IEEE Power Engineering Review 22 (12) (2002) 59.

[38] W. Rosehart, C. Canizares, V. Quintana, Optimal power flow incorporating voltage collapse constraints, Proc. IEEE PES Summer Meeting. Conference Proceedings, 2 Edmonton, 1999, pp. 820–825.

[39] W.D. Rosehart, C.A. Canizares, V.H. Quintana, Multiobjective optimal power flows to evaluate voltage security costs in power networks, IEEE Trans. Power Syst 18 (2) (2003) 578–587.

[40] F. Alvarado, I. Dobson, Y. Hu, Computation of closest bifurcations in power systems, IEEE Trans. Power Syst 9 (2) (1994) 918–928.

[41] G. Chen, D.J. Hill, X. Yu, Bifurcation Control, Theory and Applications, Springer, Berlin, 2003.

[42] M.M.A. Abdelaziz, E.F. El-Saadany, Determination of worst case loading margin of droop-controlled islanded microgrids, Int. Conf. Electric Power and Ener. Conv. Syst, Istanbul, 2013, pp. 1–6.

[43] F.W. Mohn, A.C.Z. de Souza, Tracing PV and QV curves with the help of a CRIC continuation method, IEEE Trans. Power Syst 21 (3) (2006) 1115–1122.

[44] H. Mehrjerdi, S. Lefebvre, M. Saad, D. Asber, A decentralized control of partitioned power networks for voltage regulation and prevention against disturbance propagation, IEEE Trans. Power Syst 28 (2) (2013) 1461–1469.

[45] M.R. Monteiro, G.F. Alvarenga, Y.R. Rodrigues, A.C.Z. de Souza, B.I.L. Lopes, M.C. Passaro, M. Abdelaziz, Network partitioning in coherent areas of static voltage stability applied to security region enhancement, Int. J. of Electric Power &Ener. Syst 117 (2020) 105623.

[46] E. Riccietti, S. Bellavia, S. Sello, Sequential linear programming and particle swarm optimization for the optimization of energy districts, Engineering Optimization 51

(1) (2019) 84–100.

[47] R.A. Jabr, Robust Volt/VAr control with photovoltaics, IEEE Trans. Power Syst 34(3) (2019) 2401–2408.