Journal of Engg. Research Vol. 7 No. (4) December 2019 pp. 178-202

# A Comprehensive Review on Impact of Wind and Solar Photovoltaic Energy Sources on Voltage Stability of Power Grid

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## ABSTRACT

The concern for ever-increasing demand for electricity, progressive depletion of fossil fuels, reduction in carbon footprint, improved infrastructure reliability, etc. have encouraged the power utility companies to adopt renewable energy sources in conventional power systems. The enhanced penetration of non-dispatchable renewable energy sources such as solar photovoltaic (PV) and wind energy into existing distribution and transmission networks had led to various issues of concern regarding system voltage stability. This paper presents the important issues such as voltage stability based optimum locations and sizing of distributed generation (DG) units, voltage stability assessment, and improvement techniques. The impact of power system devices such as fixed capacitors, flexible AC transmission system (FACTS), and energy storage system (ESS) on voltage stability of transmission and distribution networks are also investigated. The review results provide a comprehensive background for the voltage stability investigation in non-dispatchable renewable integrated power systems with major outcomes and findings of future research work in the field of power system stability.

**Keywords:** Power system stability; wind energy; solar photovoltaic systems; static VAr compensators; energy storage systems.

## ABBREVIATIONS

| | | | |
|---|---|---|---|
| AA | Affine Arithmetic | MIMO | Multi input and multi output |
| AVRs | Automatic voltage regulators | MINLP | Mixed integer nonlinear programming |
| BESS | Battery energy storage system | MPC | Model predictive control |
| BFOA | Bacterial foraging optimization algorithm | MSC | Mechanical switched capacitor bank |
| BTS | Brazilian test system | NLP | Nonlinear programming |
| CCP | Chance constraint programming | OLTC | Online tap changer |
| CPF | Continuation power flow | PCC | Point of common coupling |
| CSP | Concentrated solar power | PDF | Probabilistic distribution function |
| DFIG | Doubly fed induction generator | PMU | Phasor measurement unit |
| DG | Distributed generation | PSO | Particle swarm optimization |
| DSTATCOM | Distributed static compensator | PV | Photovoltaic |
| DVAR | Dynamic volt amp reactive | RSC | Rotor side converter |

| | | | |
|---|---|---|---|
| DVCI | Dynamic voltage collapse indicator | SCC | Short circuit capacity |
| EDF | Empirical distribution function | SFLA | Shuffled frog leaping algorithm |
| ESS | Energy storage system | SMES | Superconducting magnetic energy storage |
| FACTS | Flexible AC transmission system | SNB | Saddle node bifurcation |
| FC-TCR | Fixed capacitor- thyristor controlled reactor | S-NLP | Stochastic nonlinear programming |
| FRC | Fully rated converter | SRSM | Stochastic response surface method |
| FRT | Fault ride through | STATCOM | Static synchronous series compensator |
| FSIG | Fixed speed induction generator | SVC | Static Var compensator |
| GA | Genetic algorithm | SVM | Support vector machine |
| GSC | Grid side converter | TC | Transformer tap changer |
| HPSO | Hybrid particle swarm optimization | VAR | Volt ampere reactive |
| ICA | Imperialist competitive algorithm | VIR | Voltage instability risk |
| IMM | Impedance modulus margin | VSC-HVDC | Voltage source converter based high voltage direct current |
| LTVS | Long term voltage stability | VSCOPF | Voltage stability constraint optimal power flow |
| LVRT | Low voltage ride through | VSI | Voltage stability index |
| MCS | Monte Carlo simulation | VSM | Voltage stability margin |
| MERC | Modified equivalent reactance compensation | VSPA | Voltage stability probabilistic assessment |

## INTRODUCTION

For the last two decades, power system stability has been recognized as a major challenge for power system engineers (Kundur, 2011). Around the world, the occurrence of blackouts from 1965 to 2017 has shown its significance. Historically transient instability of the system was assumed to be a major cause of blackouts. This is one of the mechanisms for loss of large portion of the grid due to inability of generators to maintain synchronism during disturbances. From blackout studies, it was found that voltage instability has also been recognized as a major cause behind several blackouts (Glavic et al., 2012). Voltage stability is a local phenomenon and driven by load characteristics. According to IEEE/CIGRE joint task force report, "*Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition*" (Kundur, et al., 2004). Modern power systems are operating close to their stability limit due to economic reasons. Recently, government's new energy policies, sluggish transmission expansion, and environmental constraints have encouraged the electrical utility companies to move towards the cleaner generation technologies as wind, solar, geothermal, biomass, etc. Due to the rapid increase in the installed capacity of renewable power generation, a comparison between present and future grids is shown in Figure 1. Over the last few years, the installed capacity of wind energy and solar photovoltaic has increased drastically (Figure 2). The high penetration of these resources into existing power systems is expected to have a significant impact on power system stability. As compared to conventional power plant, renewable based generation utilizes a different set of technologies for electricity generation and interconnection with the grid. Wind turbines of type III and type IV utilize power electronics based inverter for delivering the power to the grid. Solar photovoltaic system generates D.C. electricity and an inverter is required for connection with the grid. Inverters have no moving parts and often identified as having zero inertia because their response during disturbances depends upon the specific control scheme they utilize during grid interaction.

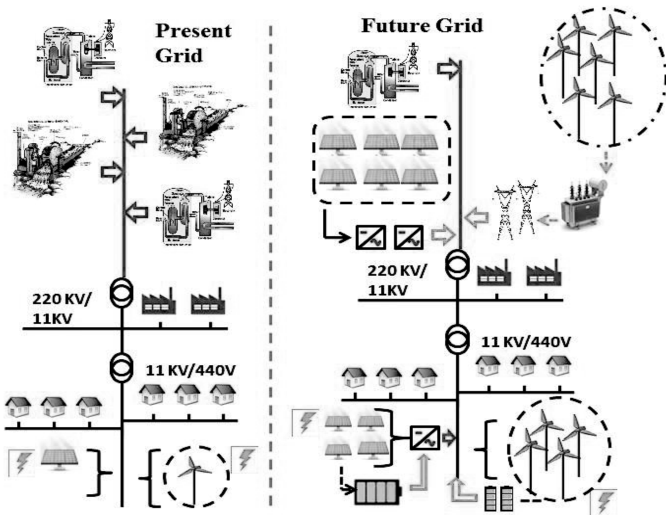


**Figure 1.** A scenario representing present and future electrical grid.

In the future, during the large injection of PV and wind power sources into the system, the stability of power system needs to be maintained for smooth operation of the system. A comparison between different generator types and capability of grid stability is shown in Table 1.

**Table 1.** Summary of generator types and capability of grid stability.

| Sr. No | Generator Type | Active power control | Reactive power control | Inertia | FRT capability |
|---|---|---|---|---|---|
| 1 | Conventional generator | ✓ | ✓ | ✓ | ✓ |
| 2 | FSIG wind turbine generator | ✓ | × | ✓ | × |
| 3 | DFIG wind turbine generator | ✓ | ✓ | × | ✓ |
| 4 | FRC wind turbine generator | ✓ | ✓ | × | ✓ |
| 5 | Standalone photovoltaic system | ✓ | ✓ | × | ✓ |
| 6 | Grid connected photovoltaic system | ✓ | ✓ | × | ✓ |
| **7** | Grid connected energy storage system | ✓ | ✓ | × | ✓ |

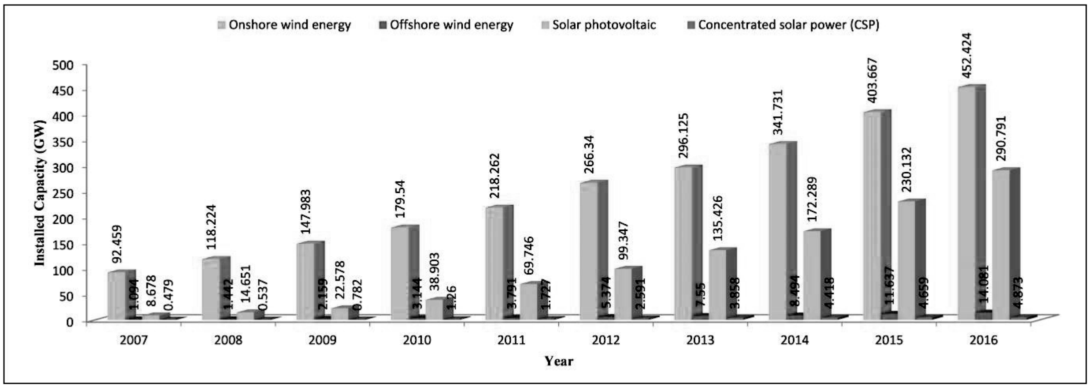


**Figure 2.** Worldwide installed capacity of grid connected wind and solar energy.

The voltage stability problem may vary from few seconds to tens of minutes and therefore, it may be short term or long term phenomenon. Analysis of short term voltage stability requires the solutions of appropriate differential equations, whereas long term voltage stability can be analyzed using static as well as dynamic methods. A comprehensive review of voltage stability indices (VSIs) has been presented in Modarresi et al. (2016). These indices are primarily used for detecting weak lines or buses in the system and can also be used for DG placement and sizing or activating countermeasures against voltage instability. A comprehensive review of optimal DG placement and sizing with objectives of power loss minimization, voltage stability enhancement, and voltage profile improvement, etc. has been highlighted in Sultana et al. (2016). In Shah et al. (2015), the authors have investigated several power system stability issues related to the large scale penetration of solar PVs. In Xu et al. (2017), a review of current methodologies for probabilistic based small signal stability analysis with a large scale wind integration had been investigated. Although few review articles have been published in recent years either on voltage stability indices or wind/solar integration studies on power system stability, none of the articles had reviewed the effects of large penetration of non-dispatchable renewable resources, i.e., wind and solar photovoltaic on system voltage stability.

This review article is consolidated as follows: section 2 reviews optimal location and sizing of DGs in distribution networks considering system voltage stability. Section 3 investigates the impact on system voltage stability with large penetration of wind and solar PV sources. In section 4, various techniques/methodologies used for assessment of voltage stability in renewable integrated transmission/distribution networks have been discussed. Methodologies for enhancement of system voltage stability are investigated in section 5. Finally, section 6 concludes the critical review points, observations, and future exploration of reviewed area.

## VOLTAGE STABILITY CONSIDERATION FOR OPTIMAL PLACEMENT AND SIZING OF DG

Depending upon the availability of natural resources, the electrical power generated from renewable sources may be connected at distribution (low or medium voltage) or transmission networks. The DG technologies that can provide electricity to customers at reasonable prices without compromising the security and reliability of the distribution network have huge potential (Atwa et al., 2010). The integration of DG units at appropriate locations into a distribution network plays a critical role in improving system performance, i.e., power loss minimization, voltage profile improvement, enhancement of system stability and loadability limit, etc. A comparison of classical and meta heuristic techniques for optimal location and sizing of DG units in distribution networks was reviewed in Prakash et al. (2016). Authors had also addressed new optimization techniques as shuffled frog leaping algorithm (SFLA), imperialist competitive algorithm (ICA), bacterial foraging optimization algorithm (BFOA), etc. for the solution of the DG placement problem. In the literature, the issue of optimal location of DG has been solved with different objective functions (Figure 3). The voltage stability assessment techniques, i.e., PV/QV curve, Modal, and Bifurcation analysis, have been used by researchers for optimal location of DGs. In Tamimi et al. (2012), it has been investigated that the penetration level of power output from wind farms can be increased by placing wind farms at voltage strong buses. Also, the additional penetration level can be increased by using static VAR compensator (SVC) at weak buses of the network. The locations of voltage strong or weak buses were located using the QV curve method.

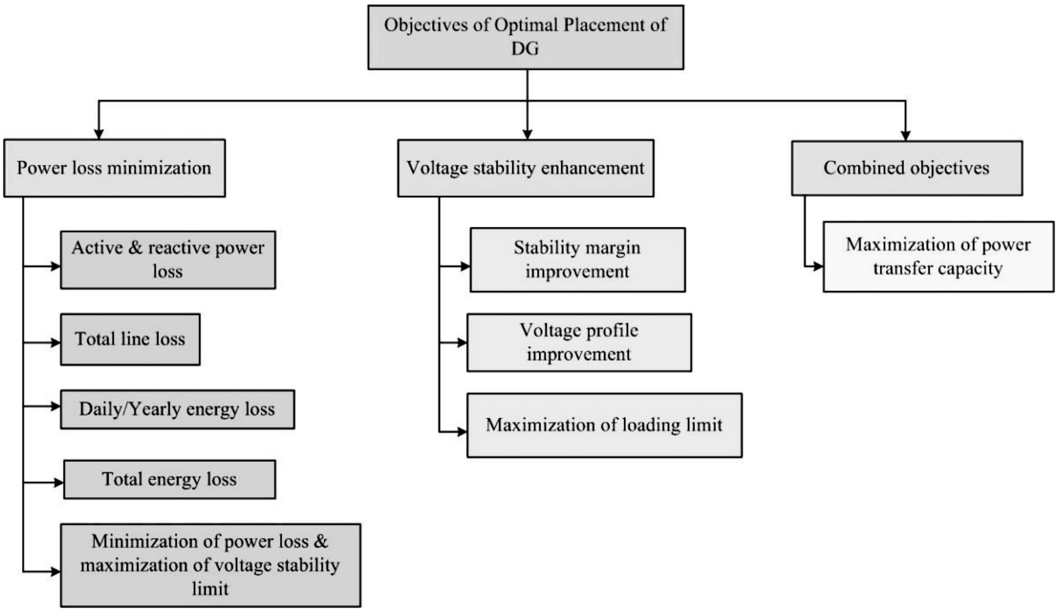


**Figure 3.** Classification of optimal DG placement objectives.

Optimization techniques such as mixed integer nonlinear programming (MINLP) (Al-Abri et al., 2013), multi-objective nonlinear programming (NLP) (Esmalili et al., 2013), dynamic programming search method (Esmaili et al., 2014), hybrid particle swarm optimization (HPSO) (Aman et al., 2014), imperialistic competitive algorithm (ICA) method (Poornazaryan et al., 2016), Monte Carlo simulation (MCS) embedded genetic algorithm (GA) (Liu et al., 2011), and weighted aggregation particle swarm optimization (PSO) (Kayal et al., 2015) were used in the literature for optimal location and sizing of DG considering voltage stability improvement of distribution network. All these studies are summarized in Table 2 for clear perception.

## IMPACT ON SYSTEM VOLTAGE STABILITY WITH NON-DISPATCHABLE RENEWABLE ENERGY SOURCES

The low inertia response and intermittent characteristics of renewable energy sources (i.e. Solar PV and wind) have increased the complexity of the conventional power system. The increased penetration of these energy resources has transformed the inherent characteristics of the conventional power system and also have considerable effect on dynamic behavior of various power system devices. Today large size wind farms of several MW capacities are being connected to the high voltage network and their impact on the system is becoming more pronounced due to large reactive power demand. The large consumption of reactive power with FSIG based wind farms had resulted in increased power loss and also had an adverse effect on system voltage stability (Ha et al., 2004). In Zhou et al. (2005), authors have investigated the effect of different parameter variations on voltage stability and applied control strategies to wind power plant model. The maximum penetration limit of the wind farm was found to be 20% of the SCC for the stable operation. In Han et al. (2008), the size and location of the STATCOM are determined by the use of PV and QV curve of system for a large wind farm integrated with weak power systems. In Inwai et al. (2005), the authors have compared the steady state voltage profile and LVRT capability of wind farms integrated with various reactive power compensation devices such as FC-TCR and SVC. In Kehrli et al. (2003), the performance of SVC, STATCOM, and DVAR integrated with wind farm for steady state and transient performance of wind farms had been explored. In Saad-Saoud et al. (1998), reactive power and voltage control schemes for STATCOM were investigated in wind integrated power system. In Liu et al. (2018), a multi-stage planning for aged equipment retirement and STATCOM placement to enhance short term voltage and LVRT capabilities of wind turbines under dynamic load scenarios has been presented.

In Liew et al. (2002), it is shown that, by implementing active network control such as generation curtailment, reactive power control and coordinated control of OLTC for voltage regulation within a distribution network increase the total installed capacity of DG. In Aly et al. (2014), Kawabe et al. (2015), and Kawabe et al. (2017), the dynamic behavior of solar PV system during voltage sags or fault conditions is highlighted. Tamimi et al. (2013) proved the fact that distributed PV generations are found to be more effective in improving system voltage stability with respect to the centralized PV generation. In Tan et al. (2007), Xue et al. (2011), and Yan et al. (2012), dynamic studies with an abrupt change of system parameters as irradiance, temperature, etc. have been carried out to analyze the impact of large penetration of PV generation into the power system. In Eftekharnejad et al. (2013), the impact of residential roof top PVs and utility scale solar PVs on a large interconnected power system is studied. It is observed that, during disturbances, higher solar PV energy penetration results in greater voltage dips and also loss of distributed PVs in a certain geographical area results in more oscillations. All these studies are summarized in Table 3 below.

## VOLTAGE STABILITY ASSESSMENT TECHNIQUES FOR SYSTEMS WITH NON-DISPATCHABLE RENEWABLE SOURCES

In the literature, the authors have proposed and implemented various static and dynamic techniques for assessment of voltage instability. Static techniques utilize Newton Raphson based power flow equations for assessment of long term voltage stability (LTVS). However, dynamic methods utilize time domain simulation with mathematical modeling of various power system components, e.g., tap changing transformers, generators, governors, and automatic voltage regulators (AVRs) for assessment of both short and long term voltage stability (Cutsem, 2000).

Plotting P-V and Q-V curves at selected load buses are the most widely used methods for assessment of voltage stability (Ajjarapu 2009). The P-V curve can be plotted at load buses using repetitive load flow solution by increasing load in steps until solution diverges. The system load at which Jacobian of Newton Raphson method becomes singular is the maximum loading point. The divergence of load flow solutions was resolved by the continuation power flow (CPF) technique. It depends on reformulating the load flow equations and applying a locally parameterized continuation technique (Ajjarapu et al., 1992). A salient feature of CPF is that it remains well conditioned at and around the critical point (maximum loading point). The general idea of CPF algorithm is given as follows.

$$f(\delta, V, \lambda) = 0 \qquad 0 \le \lambda \le \lambda_{critical} \tag{1}$$

where δ and V represent the vector of voltage angles and magnitudes at buses, respectively. Parameter λ is a scaling factor and used to generate different scenarios for loads and generator power outputs according to following equations.

$$P_{G_K} = P_{G_K}\left(1 + \lambda M_{G_K}\right) \tag{2}$$

$$P_{L_K} = P_{L_{Ko}} + \lambda\left(M_{L_K} S_{\Delta base} \cos\theta_K\right) \tag{3}$$

$$Q_{L_K} = Q_{L_{Ko}} + \lambda\left(M_{L_K} S_{\Delta base} \sin\theta_K\right) \tag{4}$$

where $P_{LKo}$ , $Q_{LKo}$ are the base case real and reactive power at load bus k, respectively, $M_{LK}$ is a multiplying factor which indicates the rate of change in load power at bus k as λ changes, $\theta_K$ is the power factor angle of load at bus k, and $S_{\Delta base}$ is the base value of apparent power.

In Flatabo et al. (1990), the sensitivity of bus voltage with respect to reactive power variation as a tool for assessment of voltage stability is done. Based on eigenvalues and corresponding eigenvectors of reduced Jacobian matrix, a modal analysis technique is proposed in Gao et al. (1992) for voltage stability assessment in larger power systems. Modal analysis technique is an indirect method for calculating dV/dQ sensitivities. For voltage stability assessment, several voltage stability indices (VSIs) have been proposed in the literature for finding the margin between current operating point to a critical point. In Modarresi et al. (2016), a comprehensive review for VSIs is classified in bus voltage stability indices (VSIs), overall VSIs, and line VSIs. Other methods (e.g., Bifurcations, direct methods, energy functions, etc.) for assessment of voltage stability margin can be found in the literature (Ajjarapu et al., 1992; Dobson et al., 1993; Alvarado et al., 1994; Overbye et al., 1991; Overbye, 1993). For finding the loadability limit of system, various authors in the literature have formulated it as an optimization problem. Different optimization techniques have been used for finding the maximum loading point (EL-Dib et al., 2006; Kuru et al., 2015; El-Keib et al., 1995; Popovic et al., 1998, Mu-Chun et al., 1999; Tso et al., 1995, Tso et al., 1996; Sajan et al., 2015).

In recent years, wide deployment of phasor measurement units (PMUs) in power systems had opened a new perspective for developing advanced voltage stability assessment techniques. The methods based upon measurements can be classified as follows.

1. Measurement gathered at one location (Vu et al., 1999; Smon et al., 2006;Corsi et al., 2008; Wang et al., 2011)
2. Wide area monitoring (Liu et al., 2014; Glavic et al., 2009; Glavic et al., 2009; Beiraghi et al., 2013; Mohammadi et al., 2015; Diao et al., 2009).

In Liu et al. (2015), wide area synchrophasor based measurement is used for LTVS detection in FSIG based wind farm integrated in the distribution network. Figure 4 shows the measurement based equivalent model of FSIG interconnected to the grid. The proposed VSI is formulated as follows.

$$SLVSI = \left| \frac{Z_t + Z_g}{Z_W} \right| \tag{5}$$

where SLVSI is synchrophasor based long term voltage stability indicator, $Z_t$ is the impedance of the transmission line, and $Z_g$ is time variant FSIG equivalent line impedance.

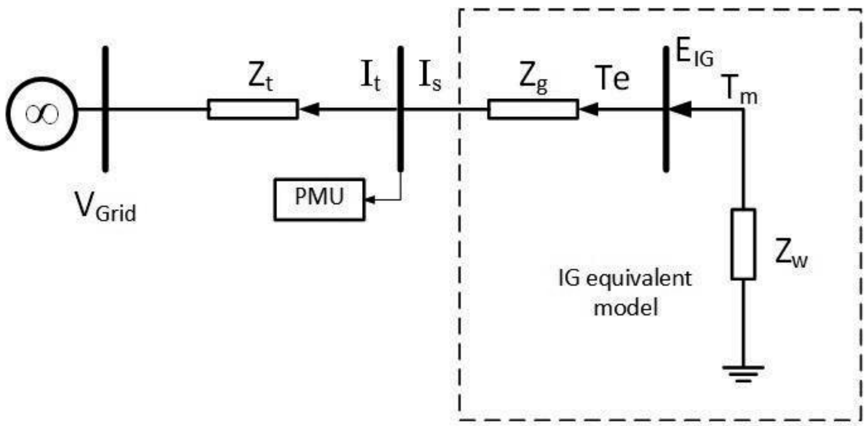


**Figure 4.** The equivalent model of FSIG connected to the grid.

**Table 2.** Comprehensive details of optimal placement and sizing of DG based on voltage stability.

| Authors | Problem Variables | | Objective Functions | | | Method | Test System | Major Outcomes |
|---|---|---|---|---|---|---|---|---|
| | Optimal location | Optimal size | Power loss minimization | Voltage Stability Improvement | Voltage profile Improvement | | | |
| Tamimi et al., 2012 | ✓ | ✓ | × | ✓ | × | Modal analysis, QV curve | Western Kansas 300 bus power system | • The buses which had lower contribution for the mode of voltage instability were considered to be the optimal location for wind farms.<br>• Use of SVCs on weak buses of the system had further increased the wind energy penetration. |
| Al-Abri et al., 2013 | ✓ | ✓ | × | ✓ | ✓ | Mixed integer NLP, modal analysis | 41 node distribution test system | • For system voltage stability margin improvement, DGs operating at unity power factor were placed on most voltage sensitive buses.<br>• The suitable location of DG units operating between 0.95 lead & 0.95 lag were found at the upper branch of the radial distribution network. |
| Ettehadi et al., 2013 | ✓ | × | × | ✓ | ✓ | Modal analysis, CPF, MERC method | 33 bus distribution test system | • Candidate locations for DGs placement were selected using modal analysis and CPF techniques while the best location for DG is selected based on a maximum loading parameter.<br>• MERC method is used to rank best DG location during reactive power shortage. |
| Esmaili, 2013 | ✓ | ✓ | ✓ | ✓ | ✓ | NLP, Fuzzy logic | 34 bus distribution radial test system | • A multi objective NLP algorithm is used for placement and sizing of DGs with combined objectives, i.e., power losses minimization and maximizing voltage stability margin. |
| Esmaili et al., 2014 | ✓ | ✓ | ✓ | ✓ | ✓ | Bifurcation analysis, Dynamic programming search method | 34 bus distribution radial test system | • A dynamic programming search technique was used to find global optimal solution for placement of DGs with combined objectives of maximization of VSM & minimization of power losses.<br>• Considering the reactive power limits, different types of bifurcation analysis including LIB, SNB, LIDB, LISB were investigated and it was found that reactive power limits alters not only the number of required DGs but also their location and sizes. |
| Aman et al., 2014 | ✓ | ✓ | ✓ | ✓ | ✓ | Hybrid particle swarm optimization | 16, 33 and 69 bus distribution system | • Simultaneous placement of multi DG units and their optimum sizing with the objective of maximum system loadability are presented. |

Table 2 (*Continued.)*

| Authors | Problem Variables | | Objective Function | | | Method | Test system | Major Outcomes |
|---|---|---|---|---|---|---|---|---|
| | Optimal location | Optimal size | Power loss minimization | Voltage Stability Improvement | Voltage profile Improvement | | | |
| Murthy and Kumar, 2015 | ✓ | ✓ | ✓ | ✓ | ✓ | Power loss sensitivity, Power stability index (PSI) | 12 , 69 and 85 bus distribution network | • The proposed VSI method is compared with existing methods, i.e. novel power loss sensitivity and power stability index (PSI) for optimal location and sizing of DG into the power network with and without load growth consideration.<br>• DGs operating at unity and 0.9 power factor (p. f.) lagging were used for study. Much improvement was seen in voltage profile and power loss reduction when DGs at lagging p.f. was used. |
| Poornazaryan et al., 2016 | ✓ | ✓ | ✓ | ✓ | ✓ | Overall voltage stability index (OVSI), ICA method | 34 bus & 69 bus distribution test system | • OVSI, a voltage stability index was used for finding the optimal location and size of DGs with the objective to minimize active power losses and voltage stability margin improvement considering load variations.<br>• Locations of DG units were independent of load variations, whereas the size of DG units varies linearly with variation in load. |
| Liu et al., 2011 | ✓ | ✓ | ✓ | ✓ | ✓ | Chance constraint programming (CCP) framework, MCS-GA | IEEE 37 node test feeder | • To handle uncertainties such as stochastic charging and discharging of plug-in electric vehicle (PEV), power output of a wind and PV unit, volatile fuel price used by fueled DG and future growth in load, a CCP model is developed.<br>• Combination of MCS with GA is used to solve the developed CCP model. |
| Kayal and Chanda, 2015 | ✓ | ✓ | ✓ | ✓ | × | Particle swarm optimization (PSO) | 28 bus Indian rural distribution system | • Hybridization of PV and wind DGs in distribution system has provided a more improved stability index than alone wind or PV integrated into the system. |

In Venkatesh et al. (2007), a dynamic voltage collapse indicator (DVCI) based on local measurements is proposed, which reflects the possibility of voltage collapse across the feeder in wind electric generator connected distribution system. The proposed DVCI is formulated as follows.

$$DVCI = f_1\left(V_i, P_j, Q_j\right) \tag{6}$$

$$f_1\left(V_i, P_j, Q_j\right) = \frac{V_i^2\left[-\left(r_{ij}P_{ij} + x_{ij}Q_{ij}\right) + \sqrt{(r_{ij}^2 + x_{ij}^2)\left(P_{ij}^2 + Q_{ij}^2\right)}\right]}{2\left(r_{ij}P_{ij} + x_{ij}Q_{ij}\right)^2} \tag{7}$$

where $V_i$ is the sending end voltage, $r_{ij}$ and $x_{ij}$ are the resistance and reactance between bus i and j, and $P_{ij}$ and $Q_{ij}$ are real and reactive power flow at bus j, respectively. In Haque (2016), the authors have proposed a static VSI at the receiving end bus, which varies between 0 and 1 when the load changes from no load to the maximum value (at voltage collapse point).

$$VSI = \left[2\left(RP + XQ\right) - V_s^2\right]^2 - 4\left(P^2 + Q^2\right)\left(R^2 + X^2\right) \tag{8}$$

where $V_s$ is the sending end voltage, S=P+jQ is the complex power flow at receiving end, and Z=R+jX is the impedance between sending and receiving bus. In Konar et al. (2015), a large signal voltage stability index has been proposed.

$$Index = \left\{\max_{1,2,..n}\left[diag\left(J_{Ri}^{-1}\right)\Big|_{t_2} - diag\left(J_{Ri}^{-1}\right)\Big|_{t_1}\right]\right\} \times 10^3 \tag{9}$$

where $J_R = \left[J_{QV} - J_{Q\theta}J_{P\theta}^{-1}J_{PV}\right]$ is known as the reduced Jacobian matrix. In Li et al., (2016), an assessment index IMM based on the Thevenin equivalent circuit is used to measure voltage stability in the distribution system with wind plant. The proposed index IMM $(\mu_n)$ is formulated as follows:

$$IMM\left(\mu_n\right) = \frac{\left|Z_{LD_n}\right| - \left|Z_{Thev_n}\right|}{\left|Z_{LD_n}\right|} \tag{10}$$

where $Z_{LD}$=V/I is the static equivalent impedance and $Z_{Thev}$= - dV/dI is comprehensive dynamic equivalent impedance.

The power generation capacity of offshore wind farm is much larger than onshore wind farm and it can be integrated with onshore AC grid by the voltage source converter based high voltage direct current (VSC-HVDC) technology (Figure 5).

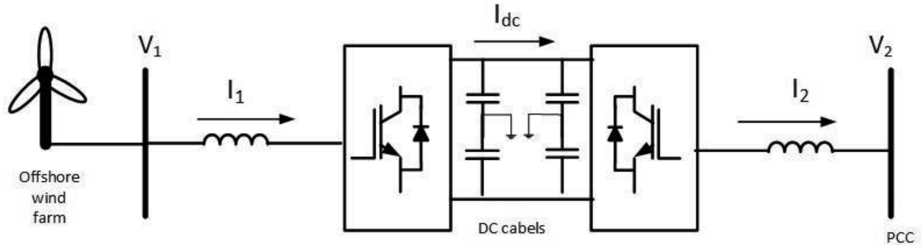


**Figure 5.** VSC-HVDC connected wind farm.

In He et al. (2014), a HVDC model is proposed for online voltage instability detection in integrated AC/DC systems by the Thevenin impedance matching. Using the "Γ" shaped equivalent model, a HVDC connected DFIG based offshore wind farm is presented in Figure 6. A dynamic model is used to represent DFIG based offshore wind farm. The symbols of $r_s$ and x' correspond to stator and transient reactance of DFIGs, respectively. $Z_T$ is the equivalent impedance of the cable and transformer system. The equivalent circuit as shown in Figure 6 can be transformed into a Thevenin equivalent circuit (Figure 7).

$$Z_{th} = \frac{\left(r_s + jX' + Z_T\right)Z_{E1}}{r_s + jX' + Z_T + Z_{E1}} + Z_{E_2} \tag{11}$$

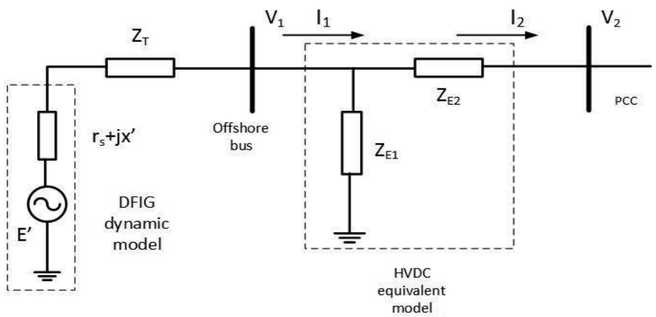


**Figure 6.** Equivalent model of HVDC connected offshore wind farm.

**Table 3.** Comprehensive details on impact of voltage stability considering large penetration of wind/solar.

| Authors | Case Study | Methods used | Test System | Major Outcomes |
|---|---|---|---|---|
| Ha and Saha, 2004 | Large wind farm connected to sub- transmission network | P-V/ Q-V curve, voltage sensitivity method, modal analysis | 14 bus radial system | • Reactive power consumption by wind farms has resulted in increased power loss and also had adverse effect on system voltage stability. |
| Zhou et al., 2005 | Wind farm connected to weak power network | Time domain simulation | Wind farm connected to infinite bus system | • System short circuit capacity (SSC) has limited the penetration of wind farm at PCC. |
| Smith and Brooks, 2001 | Distributed wind generation connected to rural distribution network | Time domain simulation | Case study of distribution network | • Apart from the uncertain wind output, the network topologies, seasonal and daily load variations are identified as fundamental causes for voltage regulation in the distribution network. |
| Han et al., 2008 | STATCOM on large wind farm connected power system | P-V/Q-V curve, Time domain simulation | 12 bus power system | • Although mechanical switched capacitors (MSCs) and transformer tap changers (TCs) can boost the steady state voltage locally, but are unable to reduce the fluctuations in voltage due to the slow dynamic response. Fast control of STATCOM can effectively suppress the voltage fluctuations. |
| Inwai et al., 2005 | Study of FRT capabilities of induction generator based wind farm with different FACTS devices | Time domain simulation | Southwest Power Pool (SPP) | • As compared to fixed capacitor, SVC is more effective in both steady state and transient stability. The FRT capability of wind farms had improved the stability and reliability of the power system under study. |
| Kehrli and Ross, 2003 | Grid integrated wind farm | Time domain simulation | Wind farm with183 turbines integrated with the utility grid (U.S.), 2 turbine wind project with grid in North Dakota | • Applications of SVC, STATCOM and DVAR are identified as the best solutions for voltage problems in a wind farm. |
| Saad-Saoud et al., 1998 | Effect of STATCOM on fixed speed wind turbine based wind farm | Time domain simulation | Wind farm of 36 x 600 KW connected to the 33 kV network | • STATCOM operating with voltage control techniques has improved the steady state voltage stability limit and also increased the penetration of power from wind farm. |
| Liew and Strbac, 2002 | Study of maximizing wind penetration in the distribution system | Linear programming based optimal power flow (OPF) | 265 node distribution system | • Application of active network control schemes such as generation curtailment, reactive power absorption, and coordinated OLTC control in distribution system could increase the installed capacity of DGs. |
| Aly et al., 2014 | Impact of large solar PV generators in distribution system | Continuous power flow method (CPF) | 33 bus radial distribution system | • Solar PV inverter with reactive power capabilities has a higher maximum loading as compared to unity power factor operated PV inverter. |
| Kawabe and Tanaka, 2015 | Impact on short term voltage stability of large solar PV system | P-V curve, Time domain simulation | One load infinite bus, 5 machine 5 load power system | • Operating the solar PV system as a leading power factor with the DVS capability can be an effective way to improve the short term voltage stability. |

Table 3 (*Continued.*)

| Authors | Case Study | Methods used | Test System | Major Outcomes |
|---|---|---|---|---|
| Kawabe et al., 2017 | Solar PV inverter with dynamic voltage support (DVS) capability for enhancement of short term voltage stability | P-V curve, Time domain simulation | 10 machine New England modified test system | • Solar PV inverter with DVS capabilities injects power as a function of terminal voltage and also enhances the short term voltage stability than conventional DVS system. |
| Tamimi et al., 2013 | Impact of centralized and distributed solar PV units on system stability | Eigenvalue analysis, P-V curve, Time domain simulation | Ontario's transmission network | • The distributed solar PV units have considerably improved the system stability with respect to centralized PV units. |
| Tan and Kirschen, 2007 | Study of dynamic response of solar PV system to rapid change in solar irradiance | Time domain simulation | IEEE 39 bus test system | • Large solar PV penetration without voltage controller has resulted in voltage fluctuations at connecting bus during large changes in irradiance. The voltage fluctuations are reduced by using constant leading power factor controller or an AVR. |
| Xue et al., 2011 | Impact of parameter variations on voltage stability in grid connected PV system | P-V curve, Time domain simulation | PV system connected to infinite bus | • Effect of temperature, irradiance and load variations on system voltage stability at the point of common coupling (PCC) is studied using sensitivity analysis. |
| Yan and Saha, 2012 | Impact on voltage stability due to high PV penetration | Time domain simulation | IEEE 13 node test feeder | • For a heavily loaded system with 40% solar PV penetration, system voltage instability occurred when the response of voltage regulator was much slower than cloud induced voltage fluctuation. |
| Eftekharnejad et al., 2013 | Impact on static and dynamic stability due to PV penetration on transmission network | Time domain simulation | Western electricity coordination council (WECC) transmission network | • Increased PV penetration level lead to alternation of the steady state voltage magnitudes and overvoltage was observed at transmission level buses. |

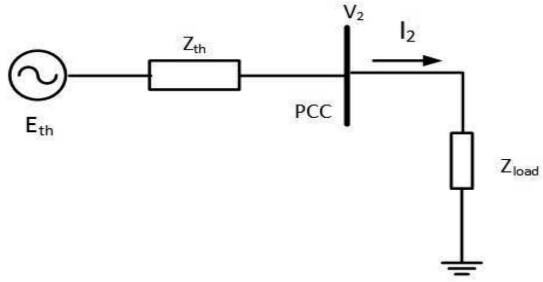


**Figure 7.** Equivalent Thevenin circuit for an integrated AC/DC grid.

The difference between the magnitude of load and Thevenin impedance i.e. $|Z_{load}| - |Z_{th}|$ can be used to determine the margin between the current operating point to a voltage collapse. The majority of techniques available in the literature have used deterministic power system parameters for voltage stability assessment. It is a valid approximation as renewable energy sources have a negligible percentage of contributions in traditional power systems. The power system with large penetration of renewable generation needs to be accounted for uncertainty and the voltage stability problem needs to be formulated as a stochastic problem. Considering the stochastic nature of the problem, various voltage stability assessment techniques are proposed by several researchers in the literature (Xiuhong et al., 2002; Kataoka, 2003; Leite et al., 2000; Haesen et al., 2009). A probabilistic based CPF considering load variation is proposed by Xiuhong et al. (2002). In Kataoka (2003), a hyper-cone model is proposed to model load variations. The proposed approach detects the loading limit on the intersection of the transfer limit surface and the hyper cone loading. In Leite da Silva et al. (2000), MCS method is used for voltage stability assessment. To reduce the computational cost, a fitting method called stochastic response surface method (SRSM) is used by Haesen et al. (2009). In Wang et al. (2013), the authors assessed voltage stability of the system in two stages. In the first stage, approximate probabilistic distribution of load margin is assessed with a minimum number of samples by use of SRSM and in second stage screening scenarios method is proposed to screen out the severe scenarios. For probabilistic voltage stability assessment, MCS is a widely used method to model a variety of system complexities (Rodrigues et al., 2010). Considering load forecast uncertainties, a cumulant based method is proposed for detection of saddle node bifurcation point (Schellenberg et al., 2006). The stochastic nonlinear programming method is used to solve the objective function, which leads to an estimation of PDF for loadability limit.

In Munoz et al. (2013), an affine arithmetic (AA) method for voltage stability assessment with IRE sources is presented. The AA based method is formulated in order to compute P-V curves and to calculate the maximum loading margin. Moreover, the proposed AA based method does not depend on PDFs associated with the uncertain variables, which is modeled as intervals with no assumptions regarding their probabilities.

In Almeida et al. (2013), with the use of P-V & Q-V curves, a probability based voltage stability assessment technique considering renewable energy sources is done. Voltage collapse and the intermittent generations are analyzed by a combination of MCS and EDF. In recent years, various researchers had published research on small signal stability assessment of the system considering large penetration of PV system (Eftekharnejad et al., 2013; Bueno et al., 2016; Liu et al., 2016) but very few authors have focused on voltage stability aspects. In Du et al. (2013), based on probabilistic optimal power flow in consideration of static voltage stability margin as a constraint, the assessment of PV penetration capacity has been investigated. In Mitsugi et al. (2014), impact of solar PV integration on multi-machine power system is studied, whereas in Verschueren et al. (2011), the voltage violations are investigated in a distribution grid with solar PV penetration. All these studies are framed in Table 4 for consolidated analysis.

## ENHANCEMENT OF VOLTAGE STABILITY FOR SYSTEMS WITH NON-DISPATCHABLE RENEWABLE ENERGY RESOURCES

Many countries in the world are developing or modifying the existing grid codes for integration of large scale renewable energy sources. The risk of voltage instability due to shortfall of reactive power support is one of the critical issues under severe contingencies in power systems. Each country has a different LVRT capability requirement of wind farm and fundamentally it demands that the wind farm must remain connected to the grid during voltage dips in the system. Fast control of reactive power from reactive power compensation devices is an essential requirement for LVRT capability of the wind farm (Hossain et al., 2014). Various techniques used in literature for enhancement of voltage stability of power system with intermittent renewable energy (IRE) sources are as shown in Figure 8.

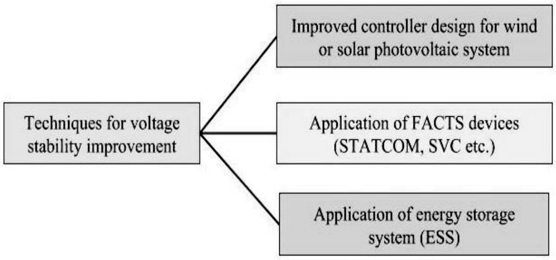


**Figure 8.** Voltage stability improvement techniques for system with renewable energy resources.

Integrating the STATCOM as compared to SVC can enhance the LVRT capability of a wind farm with squirrel cage induction generator (Molinas et al., 2008). In Roy et al. (2013), static and dynamic VAR planning are proposed based on reactive power margins for enhancement of dynamic voltage stability of the distribution system with wind DG. To calculate the margin between the current operating point to voltage collapse point, a reactive power index (Q loadability) is used. The Q loadability index is used to locate the appropriate location for compensating devices and is calculated using the equation (12).

$$Q_{loadability}(\%) = \frac{Q_{margin\_new} - Q_{margin\_old}}{Q_{margin\_old}} \times 100 \qquad (12)$$

where $Q_{margin\_new}$ and $Q_{margin\_old}$ refer to the reactive power margin of the bus before and after compensating devices, respectively. In Jiang et al. (2015), the measurement data collected from synchrophasor are utilized in support vector machine (SVM) for detecting the voltage condition of the distribution system. The controller used with wind turbine generators is actuated by the prediction results. A multi input and multi output (MIMO) auxiliary coordinated control strategy based on model predictive control (MPC) in wind turbine generator control loop is proposed (Figure 9). The proposed controller will remain inactive during normal operation. However, when a fault or other disturbances occurs the instability predictor will actuate this controller.

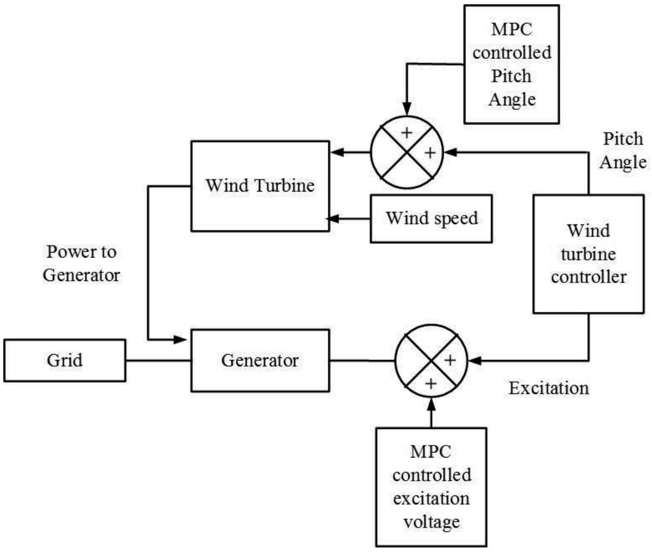


**Figure 9.** Model predictive control used in a wind turbine system.

The use of energy storage systems (ESSs) and their coordination with IRE sources (i.e., wind and solar) has been emerging as a solution in the recent years. The concept of ESS is to mitigate uncertainty in wind and solar PV generation. In this regard, the ESS technologies that have been investigated are pumped storage hydro plants, battery energy storage systems (BESS), super capacitors and superconducting magnetic energy storage systems (SMES), etc. In Le et al. (2012), a significant improvement has been shown in grid voltage stability with ESS based wind farm integration. Different energy storage systems, which could be utilized with renewable energy sources, are shown in Figure 10.

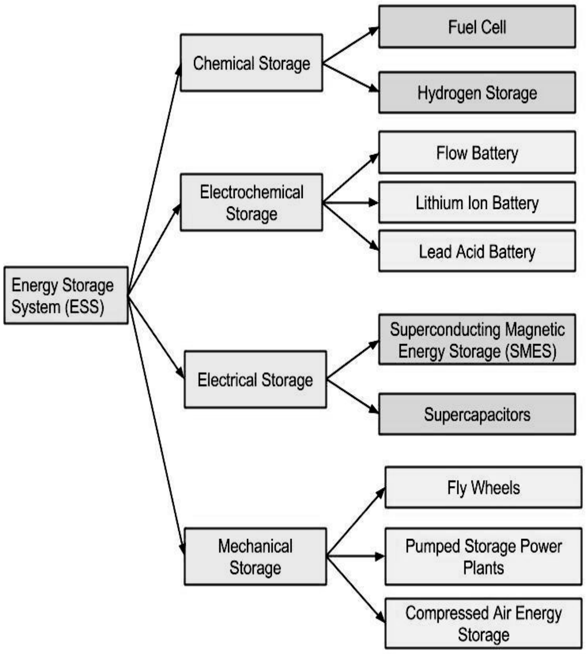


**Figure 10.** Energy storage systems used in renewable energy systems.

## CONCLUSION

In this work, a comprehensive review of system voltage stability considering non-dispatchable renewable energy sources, i.e., wind and solar PV, has been undertaken. The important outcomes from the available literature reveals the following facts:

1. Although classical voltage stability assessment methods as P-V/Q-V curves, modal analysis, CPF, etc. are being used by various researchers for optimal DG placement and sizing, due to uncertain power outputs from wind and solar PV, probabilistic based studies would provide more accurate results in finding optimal locations and sizes of DGs.

2. In literature, various optimization techniques, e.g., PSO, GA, NLP, dynamic programing, etc., have been investigated for optimal location and sizing of DG. Further, the research area can be explored by use of various combinations of hybrid optimization techniques as this will amalgamate the strengths and uniqueness of optimization techniques and produce better results.

3. The research on system voltage stability with large penetration of wind/solar PV generation is undertaken primarily for either fault conditions or/and voltage sage whereby different control techniques have been applied to the control loop of wind/ solar PV generators. However, if coordinated control of FACTS devices, e.g., SVC, STATCOM, etc., is incorporated with wind/solar energy sources, then it would enhance the voltage stability margin of the system.

4. The recent literature in the area encourages the use of advanced measuring techniques such as phasor measurement unit (PMU), which facilitates the online assessment of voltage stability in wide area measurement systems (WAMS).

5. Apart from FACTS devices, energy storage devices like BESS, SMES are also proving this mettle for improving system voltage stability. Hence, there is a need to explore the FACTS devices along with ESS for appreciable enhancement of voltage stability of the system.

**Table 4.** Comprehensive details of voltage stability assessment techniques used in systems with renewable energy sources.

| Authors | Case Study | Study type | Method Used | Test System | Major Outcomes |
|---|---|---|---|---|---|
| Liu and Chu, 2015 | Long term voltage stability detection of FSIG in distribution power network | Deterministic | Thevenin equivalent method | IEEE 13 bus, 37 bus distribution system | • Proposed an equivalent circuit of FSIG based on measurement data.<br>• Proposed an index synchrophasor long-term voltage stability index (SLVSI) for detection of LTVS problem in FSIG. |
| Venkatesh et al., 2007 | Voltage collapse indicator for wind generator in the distribution system | Deterministic | Algebraic solution of two bus system | Wind generator connected to the distribution system bus | • Proposed an index DVCI for identification of voltage collapse in distribution system.<br>• Proposed DVCI use only for local measurements in real time. |
| Haque, 2016 | Voltage stability assessment of radial distribution system with FSIG | Deterministic | Algebraic solution of two bus system | Modified 32 bus distribution system | • Proposed an index VSI for assessment of voltage stability.<br>• Improvement in VSI depends on generator size, location and reactive power support from the wind generator. |
| Konar et al., 2015 | Dynamic voltage stability assessment of power system | Deterministic | Jacobian matrix of power flow | IEEE 14 bus, IEEE 16 machine 68 bus | • Proposed a V-Q sensitivity based index for the voltage stability detection and can be used with both static and dynamic loads. |
| Li et al., 2016 | Voltage stability detection on distribution network | Deterministic | Thevenin equivalent method | Distribution network | • Proposed an IMM index for detection of voltage stability in the distribution network.<br>• The proposed index can also be used in real time. |
| He and Liu, 2014 | Identification of voltage instability in a system with HVDC integrated offshore wind farm | Deterministic | Thevnin impedance matching | IEEE 39 bus system | • PMU technology has used for calculating HVDC equivalent parameter.<br>• The HVDC equivalent model was used for online voltage instability detection and load shedding for mitigating voltage collapse.<br>• Proposed method fails to detect short term voltage stability. |
| Xiuhong, 2002 | Voltage stability study in power system | Probabilistic | Continuous power flow | IEEE 57 bus test system | • Quadratic CPF and probabilistic CPF with load variation were used with voltage stability study. |
| Kataoka, 2003 | Voltage stability assessment in power system | Probabilistic | Continuous power flow | IEEE118 bus system | • A realistic model “Hyper cone” for load parameter variation is proposed. |
| Silva et al., 2000 | Development of voltage stability indices considering the stochastic nature of the load | Probabilistic | Tangent vector method, MCS method | IEEE 24 bus RTS system | • Probabilistic method was utilized for development of voltage collapse indices based on a combination of tangent vector and MCS methods. |

Table 4 *(continued.)*

| Authors | Case Study | Study type | Method Used | Test System | Major Outcomes |
|---|---|---|---|---|---|
| Haesen et al., 2009 | Impact of intermittent sources on load margin | Probabilistic | Stochastic response surface method | IEEE 24 bus, 118 bus test system | • For assessment of load margin, a method using SRSM is presented considering non-conforming load and generation models. |
| Wang et al., 2013 | Impact of uncertain power flow on voltage stability assessment | Probabilistic | Stochastic response surface method | IEEE 24 bus, 118 bus test system | • Compared to MCS method SRSM requires a small amount of computational efforts. |
| Rodrigues et al., 2010 | Inclusion of unstable states caused by insolvability of power flow equation and voltage controllability loss in voltage stability probabilistic assessment | Probabilistic | MCS method, nonlinear optimal load flow, D' matrix method | BTS-65 system, BTS-107, Modified IEEE 24 bus system | • A method considering insolvability of power flow equations and voltage controllability loss is utilized for VSPA.<br>• Errors in forecasting of load may have a substantial effect on the VIR. |
| Schellenberg et al., 2006 | Maximum loading problem at SNB point | Probabilistic | Cumulant method | IEEE 30 bus system | • The Cumulant based method is used to solve maximum loading problem with constraint on the maximum deviation of loading parameter.<br>• An adaptation of the cumulant method to stability based S-NLP is explained. |
| Munoz et al. , 2013 | Voltage stability assessment with wind and solar power generation | Probabilistic | Affine Arithmetic | 5 bus test system, 2383 bus test system | • Affine arithmetic (AA) is proposed for voltage stability assessment.<br>• AA method is computationally more efficient than MCS method. |
| Almeida et al., 2013 | Voltage stability assessment with renewable energy sources | Probabilistic | P-V and Q-V curve, MCS, empirical distribution function (EDF) | IEEE 34 test feeder | • Reliability theory is considered for proposed voltage stability assessment methodology. |
| Du et al., 2013 | PV power penetration study considering static voltage stability | Probabilistic | Probabilistic optimal power flow (P-OPF), PSO | IEEE 30 bus test system | • The proposed method is suitable for calculating solar PV penetration limits considering the uncertainties of solar PV output and as well as the load. |
| Mitsugi and Yokoyama, 2014 | Study of PV's FRT requirement and dynamic load characteristics | Deterministic | Time domain simulation | Japan small scale 23 bus test system | • Under fault conditions, the large amount of induction motor load in power system may lead to voltage instability, but fast restoration of the solar PV generator after the fault clearing improves the stability. |

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***Submitted:*** 26/06/2018
***Revised:*** 14/11/2018
***Accepted:*** 25/12/2018

# مراجعة شاملة حول تأثير الطاقة الشمسية ومصادر الطاقة الشمسية الفولطاضوئية على استقرار الفولطية لشبكة الطاقة

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## الخلاصة

إن القلق من تزايد الطلب على الكهرباء، والنضوب التدريجي للوقود الأحفوري، وانخفاض البصمة الكربونية، وتحسين موثوقية البنية التحتية؛ وما إلى ذلك، قد شجع شركات الطاقة الكهربائية على اعتماد مصادر الطاقة المتجددة في أنظمة الطاقة التقليدية. وقد أدى الاختراق المُعزز لمصادر الطاقة المتجددة غير القابلة للامتداد مثل الطاقة الشمسية الكهروضوئية (PV) وطاقة الرياح لشبكات التوزيع والإرسال الحالية إلى العديد من القضايا المثيرة للقلق فيما يتعلق باستقرار النظام. يعرض هذا البحث القضايا الهامة مثل المواقع المُثلى المعتمدة على استقرار الفولطية وتحديد حجم وحدات التوليد المُوزعة (DG)، وتقييم استقرار الجهد وتقنيات التحسين. كما تم دراسة تأثير أجهزة نظام الطاقة مثل المكثفات الثابتة، ونظام نقل التيار المتردد المرن (FACTS) ونظام تخزين الطاقة (ESS) على استقرار الجهد في شبكات النقل والتوزيع. توفر نتائج المراجعة خلفية شاملة لاستقصاء ثبات الجهد في أنظمة الطاقة المتكاملة المتجددة غير القابلة للامتداد مع المخرجات والنتائج الرئيسية للعمل البحثي المستقبلي في مجال استقرار نظام الطاقة.