Voltage Stability in Future Power Systems

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Abstract: This chapter discusses challenges that future power systems will pose in terms of voltage stability. The focus is on the impact of the proliferation of new technological solutions. Major factors impacting voltage stability, the need for their modelling and new simulation tools are discussed including interdependency of the future power systems and other infrastructures. Probabilistic voltage security assessment to deal with increase in uncertainties is suggested. Distributed control architecture and hierarchical control for coordination are discussed and suggested as control architectures of future power systems. Synergy with developments in relevant research and engineering fields are shortly elaborated.

Keywords: future power systems, voltage stability, power electronics, uncertainty, renewable energy electricity generation.

1. Introduction

Power systems are undergoing, and will continue to undergo, considerable structural transformations. These transformations are driven by (IEEE, 2013; Monti, et al., 2020): changes in the mix and characteristics of electricity generation, changes in load types and demand profiles, emergence of smart grid technologies, new entities (such as microgrids, energy communities, etc.), energy storage technology, and increased use of FACTS devices and HVDC lines. It is reasonable to expect the future power systems will be dominated by power electronics converter-interfaced loads, energy storage, and generation from renewable energy sources. The structural transformations impact stability of power systems across all stability manifestations (angle, voltage, frequency) (IEEE, 2013) while new types of instability phenomena may arise in the converter-interface dominated power systems (Monti, et al., 2020).

Voltage stability will present one of the major challenges in the operation and control of future power systems (Monti, et al., 2020). The focus of this chapter is on how the ongoing and future power system transformations impact voltage stability and the approaches for its modelling, analysis, assessment, monitoring and control. Voltage-related problems such as fault induced delayed voltage recovery and fast temporary voltage oscillations are not considered in this chapter since it is expected that these phenomena will be much less present in the future power systems (except voltage recovery related to some generations and energy storage fault ride through capability (Shair, et al., 2021)) thanks to the use of improved power electronics interfaces for HVDC, generation, and envisioned use of power converters for induction motors responsible for delayed voltage recovery.

Future power systems will be characterized by operation under high levels of uncertainty due to increased penetration of variable energy resources and widespread deployment of locally dispatched energy storage devices. Therefore, due attention is given to the modelling of these aspects while probabilistic voltage stability analysis and security assessment, with properly handled uncertainties, is suggested as a promising approach. Smart grid technologies will enable advanced voltage stability monitoring, instability detection and control and this is discussed in the chapter together with some suggestions. Developments in other relevant fields that show potential for application in tackling voltage stability in future power systems are highlighted.

The chapter is organized as follows. Section 2 discusses the structure of future power systems and its impact on voltage stability. Basic definitions, terminology and voltage stability time scales are recalled in Section 3. Section 4 elaborates on the needs for modelling and simulation of voltage instability while Section 5 presents probabilistic stability assessment. Voltage stability monitoring, instability detection and control are discussed in Section 6. Section 7 emphasises the need for synergy with present and future developments in related scientific and engineering fields while Section 8 concludes.

2. About the structure of future power systems and impact on voltage stability

The structure of future power systems will considerably differ from the past and present ones (more from the past and less from the present structures). A structure of future power system is illustrated in Figure 1.

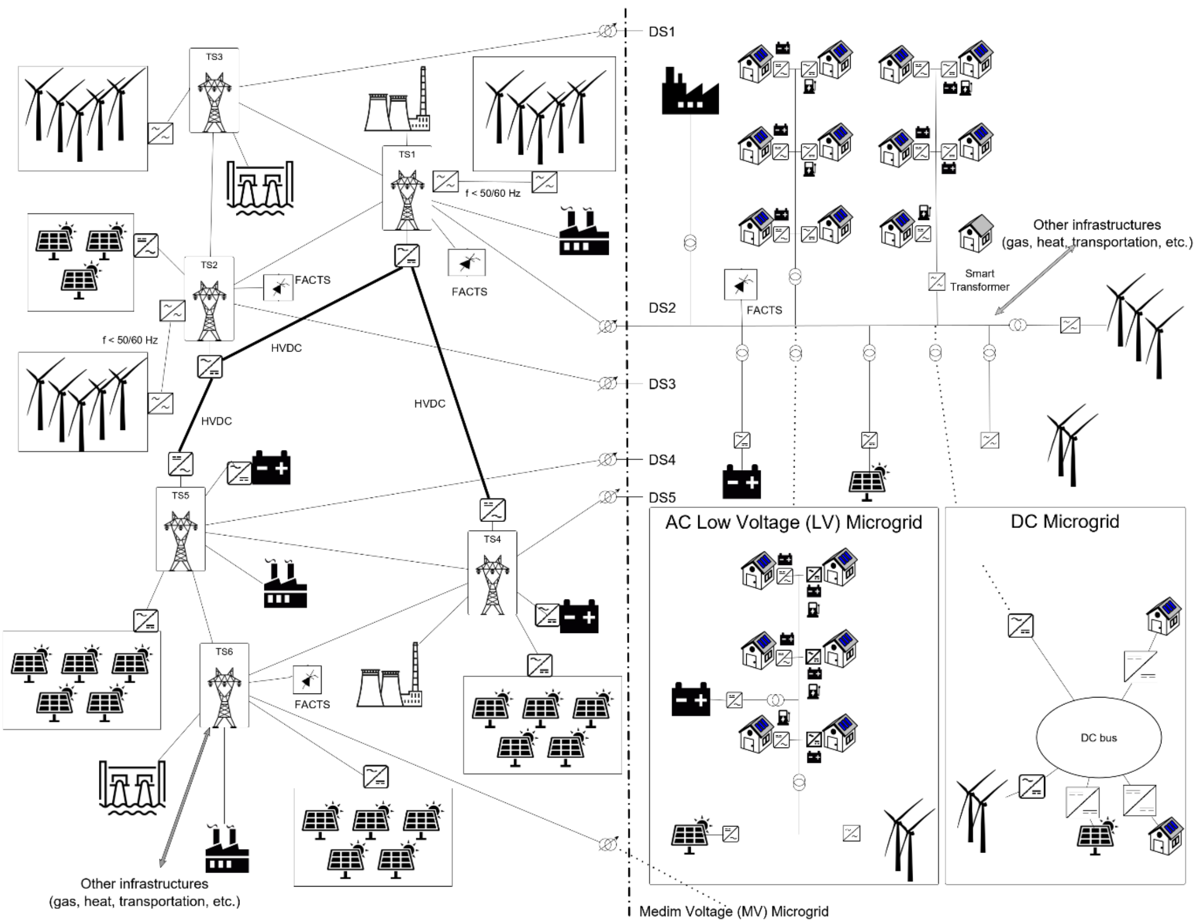


Figure 1. Power system of the future

The future power systems are characterized by (IEEE, 2013; Monti, et al., 2020):

- Widespread integration of the generation from renewable energy sources (RES), together with decommissioning of large thermal power plants, and proliferation of energy storage technologies. This integration will take place across all levels of the power system. Most new generation and storage will be power electronics converter-interfaced generation (CIG).
- Increased deployment of HVDC lines, low frequency (lower than 50/60Hz) lines and FACTS devices.
- Presence of microgrids (AC and DC) and energy communities as new entities with their own energy management systems acting according to their interests.
- New types of electricity load. The load profiles will differ considerably from the present because many loads will be aggregated as “prosumers” able to tailor consumption and generate electricity according to local conditions and their individual preferences. Typical loads will be converter-interfaced to the grid.
- Increased uncertainties in the system operation and control.
- Planning, operation, and control in the information rich environments. As a consequence of the widespread deployment of smart grid technology (advanced communications infrastructure and new instrumentation/measurement technologies), the future power systems will be cyber-physical systems.

- Massive deployment of small-scale devices (usually in low voltage networks) able to control voltage (so-called edge devices),
- Integration of power systems with other infrastructures (gas, heat, transportation) resulting in multi-carrier energy systems,
- Intercontinental connection of electricity transmission systems creating so-called "Supergrids".

Consequences of these transformations are: future power systems will exhibit multi time scale responses, nonlinearities brought by power electronics converters (discrete switching, control limiters and saturations) and increased uncertainties and sensitivities to voltage and frequency changes.

Technologies, enumerated above, will not spontaneously emerge together but instead gradually appear and revise so that the system will evolve over time. This is primarily because proliferation of any technology in power systems depends on its cost evolution over time and accumulated market volume. Based on the prices and market volume of mentioned technologies in the year of 2020, the system structure in Figure 1, discussed in the remaining of this chapter corresponds approximately to the year of 2050 and beyond.

The impacts of the above transformations of future power systems on voltage stability are summarized in Table I.

Characteristic	**Impact on voltage stability**
Massive integration of RES-based generation and electricity storage with power electronics converters.	- High uncertainties in the electricity generation, - Interaction of CIG control loops with other power system components resulting in fast and slower voltage instabilities, - The limited overload capability of CIGs for reactive power provision, - Electricity storage devices will play a key role in managing voltage critical situations, - Voltage Ride-Through (both High and Low (HVRT and LVRT)) opens possibilities for better voltage control. - Fast controls of power electronics converters require better coordination of voltage control efforts.
Presence of microgids deploying wider spectrum of technologies (including DC microgrids).	- Act on their own interests impacting operation pints of the system and its voltages, - Voltage instability is possible at the level of this entity (usually fast developing instabilities).
New type of loads and changes in load profiles.	- Power electronics interfaced loads behave as the constant power and make some controls less effective (conservative voltage reduction), - Increased uncertainties in prosumer profiles, - Need for improved load models for voltage stability studies and security assessment.
HVDC lines, low frequency lines and FACTS devices.	- HVDC might trigger fast developing voltage instability, - Low frequency lines need to be correctly represented in any voltage stability studies, - FACTS devices open possibilities for better control in voltage critical situations.
Information rich environments.	- Increased use of the data-driven voltage stability analysis and/or control,

	- Increased use of machine learning techniques for voltage stability assessment and control, - Model-free voltage stability assessment and/or control, - New challenges due to transformation of power systems to cyber-physical ones.
Integration with other infrastructures.	- Integration with natural gas and transportation infrastructures opens possibilities for improved voltage stability control, - Integration with heat and transportation infrastructure impacts voltage stability though changed load profiles.
Deployment of small-scale (edge) devices.	- Able to control voltage at low voltage level and when used in big number impact reactive power requirements.

Table I. Impact of future power system characteristics on voltage stability

The cyber-physical nature of future power systems will necessitate either a focus on physical systems with appropriate accounting of cyber impacts (e.g. considering failures in the cyber layer as contingencies) or full modelling of the system that includes both cyber and physical layers of the system. Increased uncertainties in operation and control necessitate its appropriate handling in voltage stability analysis, assessment and control.

3. Basic definitions, terminology and time scales for voltage stability analysis, monitoring and control in future power systems

Voltage stability will be one of the major challenges in future power systems planning, operation and control. For the sake of completeness, some basic definitions (Hatziargyriou, et al., 2021; Shair, et al., 2021) are repeated here.

Voltage stability refers to the ability of a power system to maintain steady voltages close to nominal value at all buses in the system after being subjected to a disturbance.

Very short-term voltage stability is one of the manifestations of fast dynamic interactions of the control systems of power electronics converters interacting with the fast-response components of the system (Shair, et al., 2021). It is specifically related to the cases when the small-signal angle instability initially originates in the voltage dynamics and voltage control stability of DC-link of power electronics converters (Shair, et al., 2021). It also refers to the fast voltage stability of line commutated converters of HVDC lines (usually experienced in HVDC line connections to weak AC grids) (Hatziargyriou, et al., 2021). This type of stability includes DC-bus voltage control stability in DC microgrids.

Short-term voltage stability involves dynamics of fast acting load components such as induction motors, electronically controlled loads, HVDC links and inverter-based generators. In future power systems (depending on the system structure and characteristics) this type of voltage stability will also involve a slow-interaction of the control systems of power electronic-based devices with slow-response components of the power system (Hatziargyriou, et al., 2021; Shair, et al., 2021) and manifested as oscillatory short-term instability.

Long-term voltage stability involves slower acting equipment such as tap-changing transformers, thermostatically controlled loads, and generator current limiters manifested in the form of a progressive reduction of voltages at some network buses (Hatziargyriou, et al., 2021) over longer time frames. While long-term voltage stability is most commonly associated with gradually declining voltages and steadily increasing load, during light loading conditions an overvoltage long-term instability can occur due to inadequate absorption of the excess reactive power.

Voltage stability analysis is the process concerned with the examination of proximity to voltage instability and mechanism of voltage instability. Properly computed *voltage stability index* is usually used as a measure of the proximity to the voltage instability while system models (static and dynamic) are used to simulate its responses in order to unveil a mechanism of the instability.

Voltage security assessment is defined as the ability of the power system to withstand any disturbance (contingency) from a pre-specified set with examination of voltage stability after the disturbances. Equipment outages, such as generator, transformer, or transmission line tripping, are considered as relevant contingencies for voltage security analysis. Dynamic voltage security assessment is based on time-domain simulation of system responses to the contingencies while static security assessment is based on static system models (usually power flow model).

The timeline of different forms of voltage stability is shown in Figure 2.

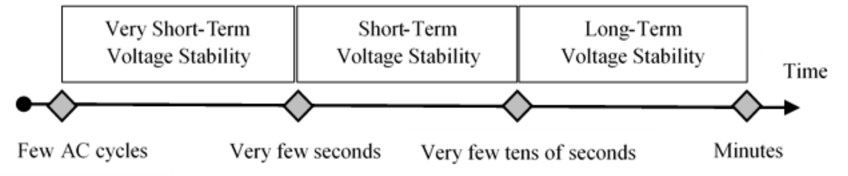
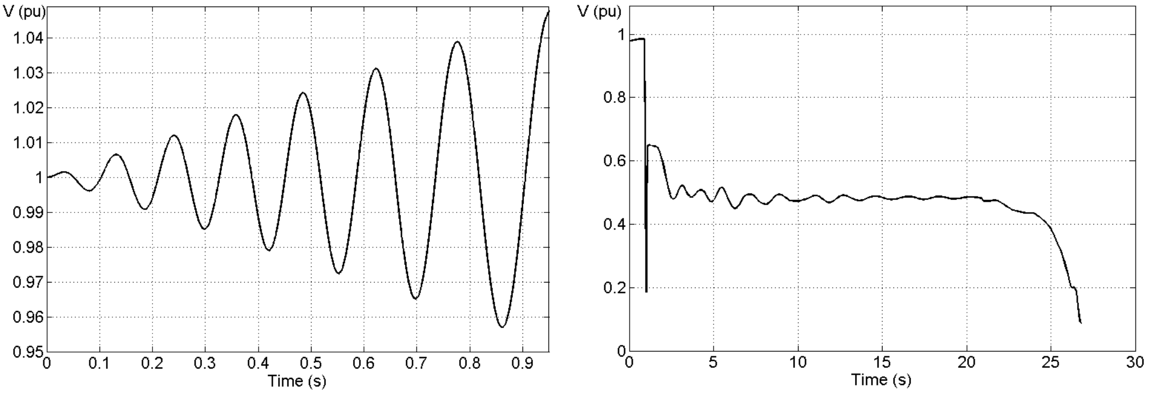
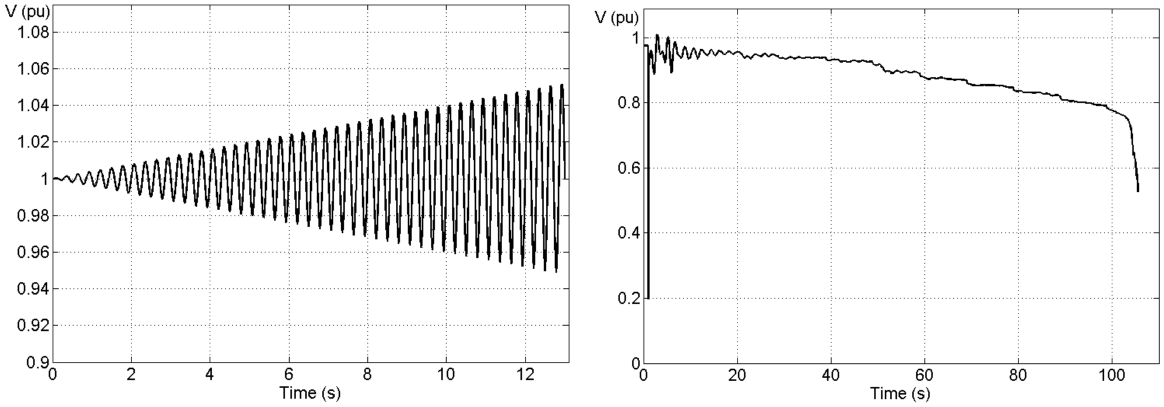


Figure 2. Time scales of voltage stability in future power systems

Manifestations of different forms of voltage instability are illustrated in Figure 3.



(a) (b)



(c) (d)

Figure 3. Typical manifestations of voltage instability: very short-term (a), short-term due to induction machine stalling (b), short-term with connection to a weak grid (c), long-term (d)

Remark: Note that we suggest very short-term voltage stability as related to fast developing phenomenon. Terms such as coverter-level, transient and dynamic voltage stability are also in use but we found these terms ambiguous since related to different phenomena in literature and bring confusion.

4. Modelling and simulation needs in future power systems

This section discusses modelling and simulation needs related to voltage stability in future power systems, focusing on the new and emerging devices and respective controls having impact on the voltage stability.

4.1 The needs for power system modelling in voltage stability studies of future power systems

This section discusses modelling needs for future power systems related to voltage stability. The focus is on identification of important aspects of emerging and expected devices that should be modelled while modelling details are available elsewhere in the literature (Monti, et al., 2020; Milano & Ortega, 2019).

Related to voltage stability, it is of paramount importance that the models include all characteristics of any device that impacts this type of stability. These characteristics are summarized in Table II and some of them further discussed in the remaining of this section.

GENERATION		
Type (general)	**Type (specific)**	**Model details**
Converter-interfaced	Wind	-Capability curve, -HVRT and LVRT, -Reactive current injection during a fault (dynamic voltage support capability) for very short-term and short-term voltage stability,
	PV	

		- Converter current limit handling in voltage critical situations (for long-term voltage stability), -Full dynamic model of the converter for dynamic studies, -Full dynamic models of associated controls (dynamic studies), -Negative loads or some extensions (for static studies).
ENERGY STORAGE		
Type (general)	**Technology**	**Model details**
Converter-interfaced	BES (battery energy storage)	-HVRT and LVRT, -positive/negative load (in charging/discharging modes, for static studies), -full dynamic model of converter with associated controls (and hard limits), -the physical laws driving the processes, -dynamic reactive power support, -state of charge.
	Supercapacitor	
	SMES (superconducting magnetic energy storage)	
	Fuel cells (hydrogen)	
	Electric spring	
	Flywheel	
LOADS		
Load type (general)	**Load type (specific)**	**Model details**
Power electronics-interfaced	Variable frequency motor drives	-In steady-state conditions could be modelled as constant power (P and Q), with linear decrease of powers between pre-specified voltage magnitude and zero bellow lower pre-specified voltage magnitude. -For dynamic simulation a complete dynamic model of the device, converter and respective controls is needed.
	Electronically commutated motors	
	EV charging stations	
	Home/building EV chargers	
Small electronic loads	Consumer electronics	-References (Arif, et al., 2018) offers some typical parameters of these types of loads.
	Appliances	
	Office equipment	
Lighting loads	Incandescent light	
	LED light	
	Fluorescent light	
	Compact fluorescent light	
Cooling/Heating	Air conditioners Heat pumps	-Induction motors are used in these devices and important to be modelled.
Prosumers	Generation (PV) + Load	-Combine models of generation (usually PV) and loads.

Table II. Some aspects of modelling of power system components in future power systems

An example of the capability curve of wind generation is shown in Figure 4 while Figure 5 displays the typical P-Q capability curve of a converter-interfaced PV generator. Most existing European grid codes explicitly or implicitly define capability curves as presented in Figure 4.

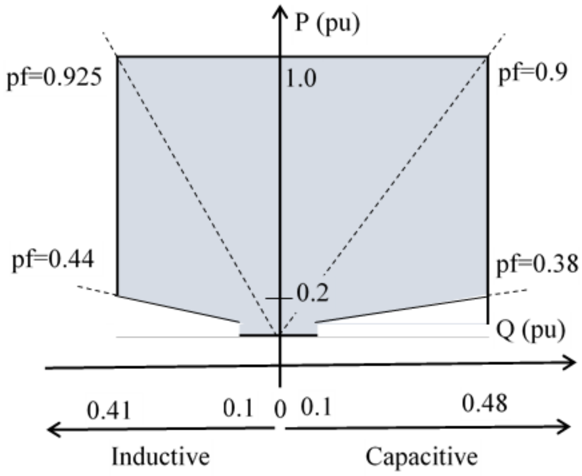


Figure 4. Wind generation P-Q capability curve satisfying most of the European grid codes

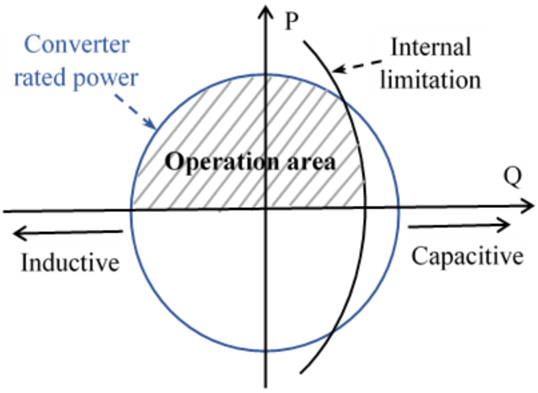


Figure 5. Basic P-Q capability curve of converter-interfaced PV generator

Note that the operating area of the capability curve displayed in Figure 5 shrinks (along the vertical axis) depending on the temperature and solar irradiance level and this dependence should be taken into account in modelling PV generations.

Other CIG characteristics important for voltage stability include: voltage control response, voltage-reactive power droop characteristic, LVRT and HVRT. Primary voltage control response of CIG (if equipped with appropriate control functionalities) is very similar to that of classical synchronous generators with the main difference being that CIG's voltage control is strictly subject to the limited conditions with no short-term overload capability. Voltage-reactive power droop characteristics are important for reactive power sharing among CIGs and unlike primary voltage control, does not maintain constant voltage at the connection point.

HVRT and LVRT capabilities of RES-based generation are important during dynamic conditions in the system and should be taken into account in dynamic models to be used in voltage stability analysis in the future power systems. These curves, as defined in IEEE Standard 1547 (IEEE, 2018), are given in Figure 6. These curves correspond to CIGs since they are expected to dominate in the future power systems.

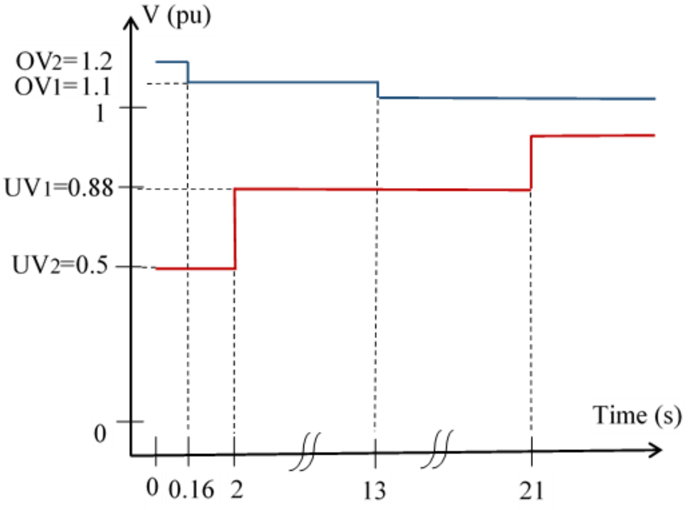


Figure 6. High and Low Voltage Ride-Through (HVRT and LVRT) as defined in IEEE 1547

Shapes of Figures 4, 5 and 6 may vary from one country to another, depending of corresponding grid codes.

In the amendment of the standard (IEEE, 2018) given in (IEEE, 2020) some values shown in Figure 6 have been changed to provide more flexibility for adoption of abnormal operating performances of CIGs. The clearing time and values of the voltage have been changed and set as given in Table III. Further research is needed for LVRT during unbalanced system conditions. In general, enhancement of LVRT (of generators and storage) leads to voltage stability enhancement.

Voltage (symbol)	Voltage value (pu)	Clearing time (s)
OV2	1.20	0.16
OV1	1.10-1.20	1.0-13.0
UV1	0.0-0.88	2.0-50.0
UV2	0.0-0.50	0.16-21.0

Table III. Suggested values for HVRT and LVRT according to (IEEE, 2020)

Related to LVRT is the capability of dynamic voltage support (through reactive current injections by the converters during a fault). While presently dynamic voltage support is required by grid codes in some countries it is reasonable to expect that these requirements will be imposed on most converter-interfaced generation in future power systems. This capability has considerable impact on voltage stability and should be properly accounted for in the models.

Loads play a crucial role in the voltage stability of power systems and their modelling significantly impacts the usefulness of voltage stability studies (Arif, et al., 2018). Proliferation of new types of loads requires re-examination/adaptation of the existing models and development of new load models. Existing load models are broadly categorized as static or dynamic. Static load models include: ZIP, exponential, and exponential with frequency dependence (although static, these models were often used in studies of a system dynamic studies). Dynamic load models include: induction motor based models (derived from the equivalent electrical circuit of the motor) and exponential recovery models. Combining static and dynamic load models led to creation of composite load models (CLM) and the most commonly used ones are: the ZIP + induction motor, complex load model (CLOD), and Western Electricity Coordination Council CLM. The identification of appropriate model parameters is the essential task in developing these models for practical use. All of these models aggregate low voltage loads up to their grid connection point. The granularity and suitability of the aggregation differs depending on the intended study. Representation of other system components, including aggregated generation, hybrid-loads, and storage, through their equivalents (static and dynamic) is a concurrent challenge intertwined with load modelling.

All load models discussed in this section are derived within the context of RMS modelling. For use in EMT-type simulations new model must be developed or the existing models adapted. Notable work is this area is presented in (Nekkalapu, et al., 2021) demonstrating load model identification for EMT-type simulations based on time-synchronized point-on-wave measurements technology.

Capturing time-varying nature of the loads (both in structure and associated parameters) is an important problem to be resolved through future research and development.

Modelling of control devices and their controls is also very important and discussed in a later section.

4.2 Emerging simulation technologies

Massive deployment of CIGs, converter interfaced energy storage, HVDC and FACTS devices together with associate controls hamper the application of traditional root-mean square (RMS or phasor-domain) dynamic models and simulations of future power systems. These models and simulations are not able to capture sub-second phenomena of CIG's converter-interfaced energy storage controls, and the complex interactions among the controls and the network, and the system response under unbalanced conditions. It is reasonable to expect that the power systems of the future will be characterized as weak ones (either as the whole system or its parts) necessitating a complete model of interface converters. A measure of a system strength relevant for voltage stability is the short-circuit ratio of the system buses and some extensions of it. Therefore, it is reasonable to expect the EMT-type of modelling and simulations will be required for dynamics studies in the future power systems while static models such as power flow and any analysis based on that will still depend on RMS assumptions (Badrzadeh, et al., 2020). EMT-type models include the network representation as individual phase voltages and currents and the details of sub-cycle controls all linked by differential equations. EMT-type simulations use numeric integration time steps of a few microseconds. As such, EMT-type models and simulations are able to capture very fast transients (for example the kHz switching frequency of power electronics devices and controls) that will be present in the future power systems. These tools are associated with high computational burdens. Considerable improvements in this respect are needed through implementation of more efficient numerical solvers and the use of advanced computational architectures (parallel and distributed computing, multi-core processors, cloud computing, FPGA, quantum computing, edge computing, etc.) (Badrzadeh, et al., 2020). On the other hand, a number of digital real-time simulators (DRTS) based on EMT-type models already exist (Guillaud, et al., 2015) and together with their future enhancements will play a key role in the simulations of the future power systems. Proliferation of smart grid technologies makes the power system cyber-physical, connected to other future cyber-physical infrastructures such as gas, heat, and transportation, creating a grand cyber-multiphysics system. The possibility of using DRTS in such systems is an additional advantage qualifying it as the likely dominant approach for the future power system modelling and simulations (Guillaud, et al., 2015).

Motivated by the success stories in aeronautics and development in advance computational architectures, communications, measurement technologies, etc., digital twin technology emerged. This technology includes a real space (physical system) and a virtual space (or a mirror of the physical system) supported by a connection system integrating data form both systems in either direction (Fuller, et al., 2020). It is expected to play an important role in future power system modelling and simulation by enabling a digital real-time simulation in a virtual space.

It is the authors' opinion that DRTS will be the dominant modelling and simulation framework for the dynamics of future power systems at the level of microgrid, energy communities and distribution systems (likely implemented in a sort of digital twin) while RMS and hybrid dynamic simulations that combine fast EMT and fast RMS simulation tools (provided that they implement fast solver on advanced computational architectures) or DRTS will serve the same purpose for transmission systems (also likely implemented in a sort of digital twin).

Due considerations should be given to the vulnerability to cyber-attacks, in particular the ones related to voltage stability monitoring and control systems.

5. Dealing with uncertainties: Probabilistic approaches for future power system voltage stability analysis and security assessment

Growing deployment of RES and expanded participation from demand side resources and distributed generation in the future power system increases uncertainty in planning and operational decision making. Explicit consideration of uncertainties is of paramount importance in operating power systems and maintaining voltage stability. Several approaches have been utilized or suggested to improve decision making under uncertainty, including: probabilistic, stochastic, possibilistic, joint probabilistic-possibilistic, information gap theory, robust optimization, and interval analysis.

Probabilistic simulation, in basic form, is the approach in which a set of (or all) inputs are modelled using their estimated probability distributions; multiple deterministic simulations are executed and the distribution of outputs analysed.
Probabilistic approaches have found application to a wide range of power system problems (for their simplicity of implementations and results interpretations). Capturing the correlation among uncertain variables is necessary for accurate risk assessment. Failure to account for high correlation among uncertain variables could lead to underestimating the risk of voltage instability. Table IV summarizes independent probability distributions for different sources of uncertainties as well as correlation modelling approaches (Hasan, et al., 2019).

Source of uncertainty	Independent probability distributions	Correlated variables	Correlation modelling
	- Normal. - Discrete normal. - Joint normal,	Wind-Wind	- Copulas (vine, Gumbel, Gaussian, Clayton, Frank),

Loads (including electrical vehicles)	- PDF of past data, - Brownian motion.		- Correlated Weibull, - Nataf transformation, - Correlated point estimate.
Power generation (in general)	- Normal, - Historical data and statistics.	Load-Wind	- Copulas (Gaussian, empirical), - Correlated point estimate, - Correlation coefficients (Pearson, Spearman), - Correlated cumulant, - Unscented transformation.
Wind generation	- Weibull, - Normal, - Discrete normal, - Gamma, - Log-normal, - Joint Gaussian	Load-Load	- Copulas (vine, Gumbel, Gaussian, Clayton, Frank, Student's), - Bivariate Gram-Charlier expansion.
Solar generation	- Weibull, - PDF of past data, - Beta.	Wind-PV	- Gaussian copula, - Correlation coefficient (Spearman).
Disturbance	- Weibull, - Bernoulli, - Poisson, - Normal, - Historical data and statistics, - Binomial, - Rayleigh, - Exponential.	Load-Wind-PV	- Gumbel copula, - Correlation coefficients (Pearson, Spearman),
Network and control systems parameters	- Normal	Parameter(s)1-Parameter(s)2	- Pair copula

Table IV. Sources of uncertainties and probability distributions

A framework for probabilistic simulations for voltage stability assessment is shown in Figure 7.

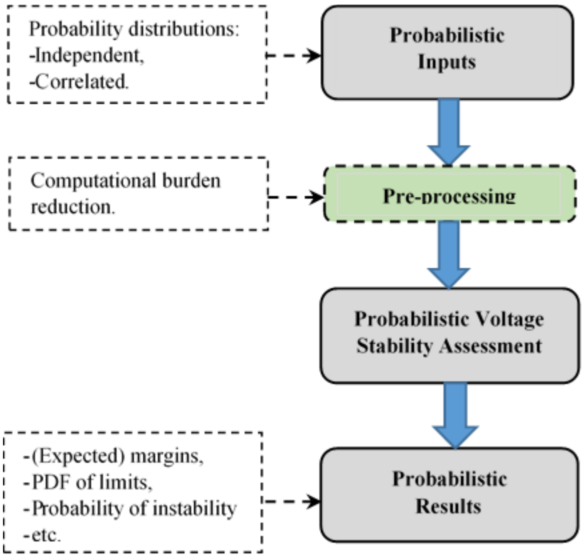


Figure 7. Conceptual framework for probabilistic voltage stability assessment in future power systems

Probabilistic methods to be used within the framework are given in Table V.

Approach	**Method (general)**	**Method (specific)**
Numerical	Monte Carlo	Quasi-Monte Carlo
		Sequential Monte Carlo
		Pseudo-sequential Monte Carlo
		Non-sequential Monte Carlo
		Scenario-based
Analytic	Based on linearization	Convolution
		Cumulants
		Taylor series expansion
		First order second moment
		Gram-Charlier expansion
		Edgeworth expansion
		Cornish-Fisher expansion
	Based on PDF approximation	Point estimate
		Unscented transformation
		Gaussian mixture
		Probabilistic collocation

Table V. Probabilistic approaches for voltage stability assessment

Probabilistic voltage stability results include (Hasan, et al., 2019): (expected) active and/or reactive voltage stability loading margin (for long-term stability), probability density function (PDF) of load increase limit (long-term voltage stability), the most probable voltage instability (bifurcation) point (long-term voltage stability), probability and frequency of voltage instability (very short-term, short-term and long-term stability), and probabilistic critical eigenvalue (short-term and long-term stability). In principle, probabilistic representation of any voltage stability index (discussed in a later section of this chapter) could be used to present probabilistic voltage stability results.

Figure 8 illustrates probabilistic voltage stability assessment for a system (with and without a single contingency) in terms of loading margin with probability density (histograms) and corresponding box-plots. One-thousand simulations were conducted on a test system using Monte Carlo method for random load increase with continuation power flow to determine the loading margin to long-term voltage instability.

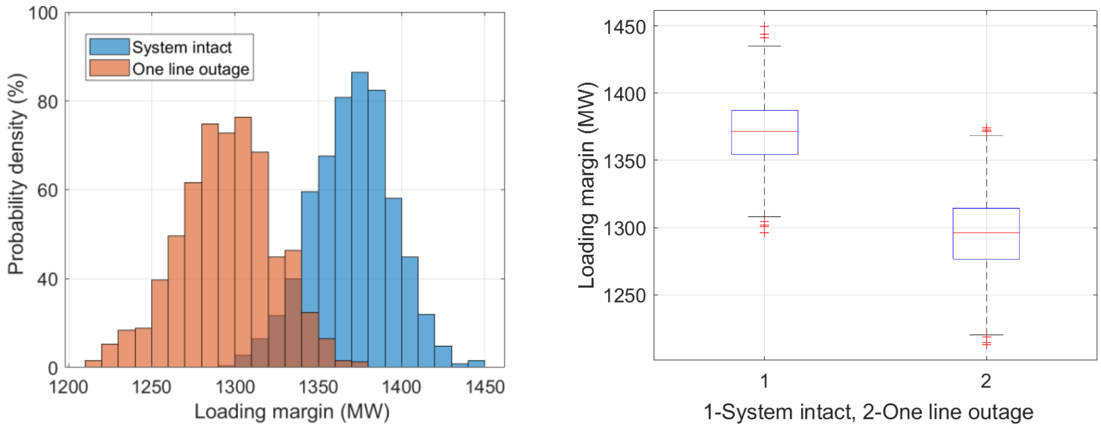


Figure 8. An example of probabilistic voltage stability assessment results

Probabilistic approaches are in general associated with high computational burden (particularly numerical approaches, even when used within a DRTS or other approaches implemented on advanced computational architectures). One option could be to use analytic approaches (particularly point estimate, cumulant-based and probabilistic collocation) since they are less computationally demanding. However, when used on large power systems with high number of uncertain variables the computational burden can still be high. This problem can be alleviated (while preserving required accuracy and assuming the use of DRTS or advanced computational architectures such as GPU, multi-core, multi-processor, FPGA, distributed computing, and cloud computing behind a simulation tool) in a number of ways (Hasan, et al., 2019):

- Prior identification of important uncertain variables to be kept throughout stability analysis,
- Dimensionality reduction through the use of equivalents of parts of the system together with prior identification of important uncertain variables of the equivalents,
- The use of efficient sampling techniques, and
- Combinations of the above.

Methods for identification of important uncertain variables include: local sensitivity analysis, global sensitivity analysis and Morris screening sensitivity analysis.

Advancements in sampling techniques for use in probabilistic voltage stability analysis include (Hasan, et al., 2019): Quasi-Monte Carlo (with low-discrepancy techniques), Latin hypercube and Latin supercube.

Probabilistic simulations will continue to be relied on for all types of voltage stability analysis and security assessment. However, other approaches under exploration such as combining stochastic process modelling with machine learning, could prove viable.

6. Voltage stability monitoring, instability detection and control in future power systems

Deep proliferation of smart grid technologies will be one of main enablers of real-time voltage stability monitoring, instability detection and control.

6.1 Voltage stability monitoring and instability detection

Voltage stability monitoring consists of measurements (local or wide-area) gathering and their processing in order to monitor the stability of the system. Voltage stability is assessed either using a carefully chosen index or the output of a proven machine learning algorithm producing a YES/NO output. Research and developments during the past several decades resulted in a number of voltage stability indices. Table VI summarizes the indices and other approaches that, in the authors’ view, have great potential to be used in future power systems for the voltage stability monitoring and instability detection.

Method (general)	Method (specific)	Voltage stability
Model-based	Modal analysis of power flow Jacobian	Long-term
	Power flow solution existence conditions derived from fixed-point theorems for accounting network structure	Long-term
	L-index and its extensions	Short-term. Long-term
	Loading margin sensitivity analysis	Long-term
	Reactive power reserves	Long-term
	Active/reactive power margins (PV/QV curves)	Long-term
	Sensitivities derived from power flow problem	Long-term
	Line stability indices	Long-term
Data-driven	SVD of measurement matrix	Short-term, Long-term
	Time series of measurements	Lyapunov exponents (Very Short-term, Short-term, Long-term)
		Critical slowing dawn (Short-term, Long-term)
	Thévenin equivalent and its extensions	Long-term
	Active/reactive power margins	Long-term
	Multi-port Thévenin equivalent	Long-term
	Decision trees based	Very short-term, Short-term, Long-term
	Deep neural networks based	Very short-term, Short-term, Long-term
	Deep reinforcement learning based	Very short-term, Short-term, Long-term

Table VI. Methods for voltage stability monitoring and detection

6.2 Voltage instability control in future power systems

Voltage instability control schemes are broadly classified as preventive and corrective. It is reasonable to expect a considerable shift toward corrective control in future power systems and the remaining portions of this section focuses on this type of controls. The corrective voltage instability controls can be designed as open loop or closed-loop. The open loop controls (or event-based) act upon recognition of a specific system state or event, and do not re-adjust the control actions determined based on off-line simulations. The closed-loop controls (or response-based) act based on the assessment of a disturbance severity, follow the system evolution and repeat control actions if previously taken were not enough to stabilize the system. A special type of corrective control is the emergency control designed to deal with extreme system conditions and usually integrated in the system integrity protection schemes. The emergency control can also be of open loop and closed-loop nature. All these controls can be organized as centralized, decentralized, distributed, and hierarchical control architectures.

Distributed control architecture will be the best fit for the structure of future power systems at the whole system level while hierarchical control for coordination (including coordination of different time scale controls) fits best at an entity level of control (to avoid interactions among controls). These control architectures are illustrated in Figure 9.

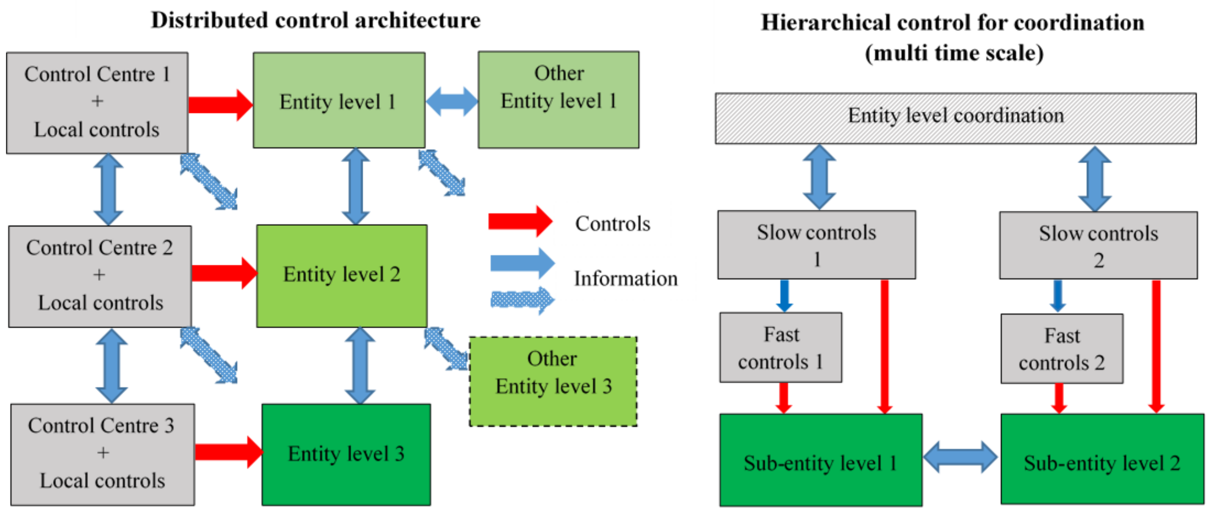


Figure 9. Distributed control architecture and hierarchical control for coordination of multi time scale systems

In distributed control architecture, the entities responsible for operation and control of a part of the system exchange information on the system state and controls with their direct higher voltage neighbours so that each of them has some knowledge about the state and controls of their neighbours (so called partially connected structure). For example, entity level 1 could be a LV microgrid, entity level 2 a distribution system or MV microgrid, while entity level 3 could be a transmission system. It is possible that in the future power systems more entities exist than portrayed in Figure 9 (for example the system could be organized in a network of smart power cells). At the level of an entity, a hierarchical control for coordination (taking into account multi time scale nature of the system) would be better fit than distributed control. The major reason for this is expectation that more control devices will be available in the future and there will be a need for their coordination to avoid negative effects of possible interactions.

The control devices, their effectiveness and applicability for different types of voltage stability (VSTVS-very short-term voltage stability, STVS-short-term voltage stability, LTVS-long-term voltage stability), their short-term overload capability (STOC) and across different future power system entity levels (T-transmission, D-distribution, M-microgrids) are summarized in Table VII (Glavic, et al., 2012).

Device	Voltage stability			STOC	Level		
	VSTVS	STVS	LTVS		T	D	M
Transformers with electromechanically controlled tap changers			*		*	*	
Transformers with solid-state tap changers		*	*		*	*	
Solid-state transformers (fully/partially rated)		*	*		*	*	*
Smart transformers		*	*		*	*	*
Synchronous generators		*	*	*	*	*	
Synchronous condenser		*	*	*	*	*	
Supervar	*	*	*	*	*	*	
RES-based generators (without converters)		*	*		*	*	*
RES-based generation (with converters)	*	*	*		*	*	*
Static var compensator (SVC)	*	*	*	* (ST)	*	*	
Switched shunt capacitor	*	*	*	*	*	*	
STATCOM (Static compensator)	*	*	*		*	*	*

Universal power flow controller (UPFC)	*	*	*		*	*	*
Transmission line switching			*		*		
Fast fault clearing	*	*			*	*	*
HVDC modulation	*	*			*		
Load shedding	*	*	*		*	*	*
Emergency demand response			*		*	*	
System sectionalizing			*		*	*	*
Energy storage	*	*	*	*	*	*	*
Energy routers		*	*			*	*
Electrical vehicles		*	*			*	*
Smart var generator	*	*	*			*	*
Connected infrastructure control (gas)		*	*	*	*	*	
Switching reactors			*(O)		*	*	
Edge devices	*	*	*			*	*
Network reconfiguration			*			*	
Networking microgrids for mutual help		*	*				*

Table VII. Voltage and reactive power devices for control in future power systems (ST-short-term for high-voltage SVC, O-overvoltage)

The devices and the modelling of their associated controls is necessary for voltage stability analysis and security assessment. Only the devices that, in the authors' view, will play important new roles in future power system voltage control are discussed in this section, i.e. smart transformers, energy storage, edge device, and converter controls.

Smart transformers are an emerging power electronics-based device capable of decoupled, nearly independent control of both the primary and secondary side, exhibiting fast voltage response times. Initial development began with LV grid application but future extension to any voltage level across the future power system is likely.

Energy storage will also play a significant role in maintaining future power system voltage stability (in particular converter-interfaced energy storage). Reference (Milano & Ortega, 2019) clearly indicates improvements across all aspects of voltage stability and across all structural levels in future power systems.

Edge devices are fast acting hybrid power electronics devices installed at the grid edges (usually LV network) with embedded artificial intelligence functionalities. These devices will be fully exploited for voltage control, together with the edge computing, in the context of future power system digitalization through the Energy Internet (the concept of the Internet of Things applied in future power systems).

Operation and control of future power systems will be, in a large extent, determined by the control concepts of power electronics converters (used across different voltage levels and devices). Voltage source converter (VSC) types are expected to dominate future power systems and they are usually classified according to their operating characteristics as: grid-following, grid-forming and grid-supporting (either of the former with $P - f$ and $Q - V$ control functions thus becoming "grid-supporting grid-following" or "grid-supporting grid-forming"). Grid-forming and grid-supporting grid-forming converters are expected to dominate in the future.

Fault tolerance is desirable characteristic for future power system controls. This would allow the design of reconfigurable control. Dealing with uncertainties in voltage controls is equally important as for other aspects of voltage stability (analysis, security assessment). In this respect the chance-constrained programming (Hajian, et al., 2012) is viable approach for future power system controls. This approach incorporates uncertainties into model through a probabilistic measure of uncertain constraints and, as probabilistic approaches discussed earlier in this chapter, assume probability density function known and requires efficient sampling (Latin hypercube suggested in (Hajian, et al., 2012)) to be compatible with real-time control requirements.

7. Synergy with present and future research and developments in relevant scientific and engineering fields

Research and development in power systems often seeks to capitalize on the most recent advances achieved in the broader fields of system and network science, applied mathematics and computer science as well as recent technological innovations in fields such as measurement and instrumentation, telecommunications, and power electronics, and current industrial trends such as the increased availability and lessening cost of powerful computational facilities, edge devices, etc. Future research and development in these fields should be closely followed and tested/used in all aspects of voltage stability of the future power systems.

Developing trends in system and network sciences research are: the system of systems concept, complex networks, networked control systems, and the control over networks. Impact of a network structure on voltage stability appears to be an important problem to be investigated in the future. In this respect, a better characterization of a system strength with respect to voltage stability appears to be needed.

Developments of algorithms in applied mathematics are strongly related to advanced computational architectures. Particularly important is development in linear algebra and the advent of new fast linear systems of equations solvers as the core of most voltage stability computation aspects.

Emerging measurement and instrumentation is time-synchronized point-on-wave technology with high-resolution (256 samples per second and more). While such a high-resolution is not needed for short- and long-term voltage stability ((micro) synchronized phasor measurements are sufficient for these purposes) it could play an important role in monitoring and control of very short-term voltage stability.

Development in power electronics converters dictates, and will continue to dictate, the developments in structure of the future power systems. Although VSC type converters are expected to dominate future power systems, increased use of Z-source and quasi-Z-source converters is likely in some future with considerable effects on the voltage stability and this possible development is to be closely followed. Strong synergy between stability assessment methods adopted in power electronics community (e.g. impedance-based stability assessment) with voltage stability assessment methods from a system level point of view is absolutely needed in the future.

There are some relevant breakthroughs in computer science such as deep learning (particularly deep neural networks) and deep reinforcement learning. Deep neural networks scale well to multi-stage decision problems in high-dimensional spaces due to their generalization capabilities. Furthermore, they are able to automatically extract most important features for specific problem. This is a very vibrant research field with new algorithms emerging at fast pace and five trends in deep learning to be closely followed for future power systems voltage stability applications include: handling limitations of currently available deep learning architectures, taking ideas from neuroscience and human brain, eliminating the need for labelled data, better transfer learning capability, learning to learn concept, self-supervised learning, physics-informed machine learning, and explainable artificial intelligence technologies. Efficient embedding of domain-specific knowledge is the key for wider acceptance of machine learning approaches in different aspects of voltage stability leading to safe learning approaches (usually neglected in machine learning research community).

Control theory and engineering research to be followed include: fault tolerant and reconfigurable control, agent-based distributed control, synergy with machine learning for design of advanced controls, efficient use of available rich information in control designs (context aware control).

In terms of communications the fiber-optic and wireless media will have increased role in the future power systems. Self-manageability, self-adaptability, and self-configuration of communications infrastructure are expected to be incorporated in the future power systems and timely considerations of these aspects is important.

New technologies will emerge including new (or renewed) electricity generation sources (not necessarily relying on the renewable energy sources) and new storage devices (in particular graphene supercapacitors). Each of these technologies bears some specifics in terms of provision for voltage stability support and the developments should be closely followed.

8. Conclusions

Voltage stability will present one of the major challenges for future power systems planning, operation and control. Realistically expected changes in the structure of future power systems will increase the importance of modelling fast-acting power electronic devices and necessitate accommodating increased uncertainties. Based on the material presented in this chapter and extensive literature search (including the works related to future trends in the fields that will considerably impact the future power systems structure and characteristics) we draw the following conclusions:

- It is essential to model all characteristics of any future power system components that impacts voltage stability. Particularly important problems to be tackled in the future are improved models of power electronics converters and their controls and limits, as well as development of EMT-type load models (static and dynamic) and equivalents of parts of the system (static and dynamic). Circuit-based modelling is expected to be dominant.
- DRTS, based on EMT-type modelling, will dominate as a simulation environment at LV and MV levels (implemented in a sort of digital twin) while a hybrid EMT-RMS approach might still prove useful for MV level. DRTS will also be very present at the HV level, while RMS (less) and hybrid (more) type of modelling and simulations will still be useful at HV level for dynamic simulations. RMS modelling and simulations will be sufficient for all voltage levels in case of steady-state analyses. All RMS models and simulation tools are expected to be realized using advanced computational architectures and implemented in a sort of digital twin.

- Uncertainties should be dealt with great care in all aspects of voltage stability. This chapter suggests probabilistic approach to deal with uncertainties for voltage stability analysis and security assessment and chance constrained optimization for voltage controls as appealing solutions.
- More data-driven approaches to voltage instability monitoring and control are expected in future power systems together with increased reliance on safe machine learning (in particular deep neural networks and deep reinforcement learning together with embedding domain-specific knowledge offering solutions for safety problems present in many machine learning approaches).
- Distributed control, likely in the form of a so-called partially connected structure, is expected to be the control architecture of future power systems at the whole system level. Hierarchical control for coordination and accounting for presence of multi time scale dynamics, at an entity level, is suggested for coordination of many control devices that will be present and possibly causing instability due to their interactions.
- The controls are expected to take full advantage of acting in information rich environment (context aware control) and fast controls enabled by power electronics converters. Fault tolerant and reconfigurable control are promising approaches to be considered for the future power system voltage instability controls (due to the cyber-physical nature of future power systems). More reliance on dynamic state estimation is realistically expected since it facilitates the design of fault tolerant controls.
- It is reasonable to expect more overlap between voltage stability and other types of stability phenomena. This suggests a holistic approach to future power system stability might be needed and new voltage stability paradigms are likely to appear in the future.
- Advancement in relevant research and engineering fields such as power electronics, control, communications, applied mathematics, and new technological solutions for electricity generation and storage should be closely followed to account for their impacts on voltage stability in the future power systems.

Although not specifically considered in this chapter, a related issue is design of efficient markets for voltage support provision due to expected increase of peer-to-peer electricity trading based on blockchain technology that will impact voltage stability conditions of the future power systems and needs to be properly accounted for.

References

Arif, A. et al., 2018. Load modelling – A review. *IEEE Transactions on Smart Grid,* Volume 9, pp. 5986-5999.

Badrzadeh, B. et al., 2020. The need for enhanced power system modelling techniques and simulation tools. *CIGRE Science and Engineering,* Volume 17, pp. 30-46.

Fuller, A., Fan, Z., Day, C. & Barlow, C., 2020. Digital twin: Enabling technologies, challenges and open research. *IEEE Access,* Volume 8, pp. 108952-108971.

Glavic, M. et al., 2012. See it fast to keep calm: Real-time voltage control under stressed conditions. *IEEE Power and Energy Magazine,* Volume 10, pp. 43-55.

Guillaud, X. et al., 2015. Applications of real-time simulation technologies in power and energy systems. *IEEE Power and Energy Technology Systems Journal,* Volume 2, pp. 103-115.

Hajian, M., Glavic, M., Rosehart, W. D. & Zareipour, H., 2012. A chance-constrained approach for control of transmission voltages. *IEEE Transactions on Power Systems,* Volume 27, pp. 1568-1576.

Hasan, K. N., Preece, R. & Milanovic, J. V., 2019. Existing approaches and trends in uncertainty modelling and probabilistic stability analysis of power systems with renewable generation. *Renewable and Sustainable Energy Reviews,* Volume 101, pp. 168-180.

Hatziargyriou, N. et al., 2021. Definition and Classification of Power System Stability – Revisited & Extended. *IEEE Transactions on Power Systems.*

IEEE, 2013. *Smart grid research: Power - IEEE grid vision 2050 roadmap,* s.l.: s.n.

IEEE, 2018. *IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces,* Piscataway: IEEE.

IEEE, 2020. *Amendment 1: To Provide More Flexibility for Adoption of Abnormal Operating Performance Category III,* Piscataway: IEEE.

Milano, F. & Ortega, A., 2019. *Converter-interfaced energy storage systems: Context, modelling and dynamic analysis.* s.l.:Cambridge University Press.

Monti, A., Milano, F., Bompard, E. & Guillaud, X., 2020. *Converter-Based Dynamics and Control of Modern Power Systems.* s.l.:Elsevier/Academic Press.

Nekkalapu, S. et al., 2021. Synthesis of load and feeder models using point on wave measurement data. *IEEE Open Access Journal of Power and Energy,* Volume 8.

Shair, J., Li, H., Hu, J. & Xie, X., 2021. Power system stability issues, classifications and research prospects in the context of high-penetration of renewables and power electronics. *Renewable and Sustainable Energy Reviews,* Volume 145, p. 111111.

Further reading

Cabrera-Tobar, A., Billuch-Massague, E., Aregues-Penalba, M. & Gomis-Bellmunt, O., 2016. Capability curve analysis of photovoltaic generation systems. *Solar Energy,* Volume 140, pp. 255-264.

Chen, J. et al., 2021. Impact of smart transformer voltage and frequency support in a high renewable penetration system. *Electric Power Systems Research,* Volume 190, p. 106836.

Ghafouri, M. et al., 2020. Detection and mitigation of cyber attacks on voltage stability monitoring of smart grids. *IEEE Transactions on Smart Grid,* Volume 11, pp. 5227-5238.

Ghazavidozein, M., Gomis-Mullmant, O. & Mancarella, P., 2021. Simultaneous provision of dynamic active and reactive power response from utility-scale battery energy storage systems in weak grids. *IEEE Transactions on Power Systems,* Volume Early Access.

Glavic, M., 2019. (Deep) Reinforcement learning for electric power system control and related problems: A short review and perspectives. *Annual Reviews in Control,* Volume 48, pp. 22-35.

Gonzalez, D. M., Myrzik, Y. & Rehtanz, C., 2020. The smart power cell concept: mastering TSO-DSO interactions for the secure and efficient operation of future power systems. *IET Generation, Transmission, Distribution,* Volume 14, pp. 247-2418.

Hanninger, S. & Jaeger, J., 2020. Advanced classification of converter control concepts for integration in electrical power systems. *International Journal of Electrical Power and Energy Systems,* Volume 123, p. 106210.

Milanovic, J. V., 2017. Probabilistic stability analysis: the way forward for stability analysis of sustainable power systems. *Philosophical Transactions of Royal Society A,* Volume 375, p. 20160296.

Misyris, G. S., Chatzivasileiadis, S. & Weckesser, T., 2021. Grid-forming converters: Sufficient conditions for RMS modelling. *Electric Power System Research,* 197(107324).

Paolone, M. et al., 2020. Fundamentals of power system modelling in the presence of converter-interfaced generation. *Electric Power Systems Research,* 189(106811).

Peng, Q. et al., 2019. On the stability of power electronics-dominated systems: Challenges and potential solutions. *IEEE Transactions on Industry Applications,* Volume 55, pp. 7657-7670.

Rabiee, A., Kamwa, I., Keane, A. & Soroudi, A., 2021. Gas network's impact on power system voltage security. *IEEE Transactions on Power Systems,* Volume Early Access.

Sourkounis, C. & Tourou, P., 2013. Grid code requirements for wind power integration in Europe. In: Y. Al-Assaf, ed. *Conference Papers in Energy.* s.l.:Hindawi Publishing Corporation.

Torabi Milani, M., Khodabkhchian, B., Mahserejian, J. & Sheshyekani, K., 2021. Development and validation of a new detailed EMT-type component-based load model. *Electric Power Systems Research,* Volume 197, p. 107290.

Zhang, G., Li, Z., Zhang, B. & Halang, W. A., 2018. Power electronics converters: Past, present and future. *Renewable and Sustainable Energy Reviews,* Volume 81, pp. 2028-2044.