A Comprehensive Toolbox for Voltage Stability Assessment of the Swiss Transmission System

Ioannis Papadopoulos, Georgia Pierrou, Asja Derviškadić, Agnes Linnet, Gabriela Hug

***Abstract*—Ensuring voltage stability remains a constant concern for power system operators. To improve situational awareness and comply with the latest directives on dynamic security assessment, this paper presents a comprehensive toolbox for conducting voltage stability assessments which is applied to the Swiss transmission power grid. A dynamic model is developed that incorporates load and generator dynamics and can accurately represent the dynamic behavior of the Swiss transmission system. The proposed toolbox integrates both short-term and long-term voltage stability indicators for the developed dynamic model. Numerical results validate the effectiveness of the toolbox in capturing voltage-related issues in areas identified as prone to voltage instability utilizing actual system data.**

***Index Terms*—dynamic security assessment, Phasor Measurement Units (PMUs), voltage collapse, voltage stability**

I. Introduction

Voltage stability, defined as the ability of a power system to maintain acceptable voltages after a disturbance, is especially important for secure power system operation. Sustained voltage deviations that are not properly addressed can escalate into a voltage collapse and large-scale power outages. Recent events, such as the voltage collapse that triggered a widespread blackout in the Balkans on June 21, 2024 [1], have underscored the serious consequences of inadequate voltage stability assessment and reignited industry interest in developing robust methods for accurate voltage stability monitoring.

Swissgrid, the Swiss Transmission System Operator (TSO), ensures system security primarily through static N-1 contingency analyses ensuring also that voltages are within safety limits. However, voltage stability is a dynamic phenomenon by nature. Accordingly, dynamic modeling and dynamic assessment are more suitable for voltage-stability analysis. At the same time, the development of Wide-Area Monitoring Systems (WAMS) provides an opportunity to leverage Phasor Measurement Units (PMUs) to advance conventional voltage stability assessment relying on model-less based approaches.

Several methods in the literature have focused on assessing both long-term and short-term voltage stability. In [2], [3], the authors suggest leveraging PMU measurements to monitor electrical quantities at boundary buses of a stressed load area, such as imported active power and apparent conductance, and propose relevant indices for detecting voltage collapse. Related methods assess proximity to voltage collapse by monitoring individual transmission lines rather than aggregated load areas [4], [5]. Short-term voltage stability and delayed recovery phenomena have been investigated by examining the dynamic response of composite loads and the stalling behavior of single-phase induction motors, which can be detected through changes in the load's susceptance following a fault [6], [7].

In this paper, a systematic approach to assess voltage stability in the Swiss transmission system is proposed. In line with the operational requirements set out in the EU System Operation Guideline concerning the establishment of dynamic models and the continuous assessment of system stability [8], a toolbox for voltage stability assessment tailored to the Swiss transmission system is developed. Hence, the main contributions of the paper are:

1) A dynamic model is developed, which can accurately represent system behavior based on actual grid snapshots of the Swiss transmission system.
2) Both short-term and long-term voltage stability considerations are integrated in the proposed toolbox.
3) A comprehensive numerical validation is conducted in the areas that are found to be prone to voltage instability with the use of actual PMU data.

The remainder of the paper is organized as follows: Section II provides an overview of short-term and long-term voltage stability assessment methods. In Section III, the dynamic model developed for the Swiss transmission system and the proposed toolbox for voltage stability assessment are described. Section IV presents the numerical results. Section V summarizes the conclusions and perspectives for future work.

II. Overview of Voltage Stability Assessment

This section provides an overview of voltage stability assessment and monitoring methods, which serve as the theoretical basis for the proposed toolbox. First, PMU-based indices that act as early indicators for long-term voltage stability issues are discussed. Then, short-term voltage stability assessment is presented, including a widely adopted representation for load dynamics to capture underlying short-term voltage instability.

A. PMU-based Long-term Voltage Stability Assessment

A PMU-based method for monitoring long-term voltage stability at any transmission bus feeding a weak area is proposed in [2]. In particular, the New LIVES Index (NLI) is proposed in the aforementioned work, which is able to

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detect voltage instability based on the continuous tracking of the imported active power and the apparent conductance of a heavily loaded area.

Briefly, assuming that a PMU is installed at the boundary bus i of a voltage-weak area, the voltage phasor $\tilde{V}_i$ and all currents $\tilde{I}_{ik}$ entering from $k \in K$ corridor buses connected to the bus are measured. Hence, the total imported current at bus i can be computed as follows:

$$\tilde{I}_i = -\sum_{k \in K} \tilde{I}_{ik}, \quad i = 1, \ldots, n \tag{1}$$

These phasor measurements are then used to calculate the imported active power P_i and apparent conductance G_i as:

$$P_i = \Re\left\{\tilde{V}_i \tilde{I}_i^*\right\} \tag{2}$$

$$G_i = \Re\left\{\frac{\tilde{I}_i}{\tilde{V}_i}\right\} \tag{3}$$

The long-term voltage stability index NLI is derived by appropriately filtering the computed quantities and taking long-term differences as follows:

$$\text{NLI}_i = \frac{\Delta P_i}{\Delta G_i} \tag{4}$$

The physical principle underlying this voltage collapse identification method is based on the relationship between demand and transmitted active power. Particularly, when a rise in demand, reflected by an increase in apparent conductance ($\Delta G_i > 0$), is accompanied by a corresponding increase in transmitted active power ($\Delta P_i > 0$), the NLI remains positive and the area is considered voltage stable. In a voltage collapse scenario, [2] shows that the transmitted active power reaches the maximum power transfer value and then declines. Yet, continued demand growth leads to a positive apparent conductance change. The combination of these two effects results in a negative value for the NLI. Therefore, a zero-crossing of the index at any of the monitored boundary buses serves as a necessary precursor to voltage collapse [9].

In addition to NLI, the Relay-based Local Index (RLI) of voltage emergency is introduced in [3]. The primary distinction between the RLI and the NLI lies in the quantity being monitored. RLI monitors the incoming current at the receiving end of a single boundary interconnection, rather than the total imported current as seen by a boundary bus, namely:

$$\tilde{I}_i = -\tilde{I}_{ik}, \quad \text{for } i = 1, \ldots, n \tag{5}$$

The RLI is then computed based on the changes in transmitted active power and apparent conductance across the monitored interconnection as:

$$\text{RLI}_{ki} = \frac{\Delta P_{ki}}{\Delta G_{ki}} \tag{6}$$

The physical interpretation of the RLI is analogous to that of the NLI. Prior to a voltage collapse, at least one boundary interconnection reaches its static transfer stability limit [10]. At that point, the transmitted active power through the line begins to decrease ($\Delta P_{ki} < 0$) while the apparent conductance continues to increase ($\Delta G_{ki} > 0$). As a result, the RLI becomes negative and a zero-crossing of the index indicates impending voltage instability.

B. Short-term Voltage Stability Assessment

One of the most relevant phenomena associated with short-term voltage instability is the Fault Induced Delayed Voltage Recovery (FIDVR) [6]. This phenomenon is particularly prevalent in regions where single-phase induction motors comprise a significant portion of the load [7]. The primary mechanism behind FIDVR is motor stalling [11]. In particular, following a fault, single-phase induction motors attempt to accelerate by drawing higher currents compared to their nominal values. This leads to an increase in reactive power demand, which further suppresses the voltage level and delays its recovery. A low-voltage condition that persists for an extended period, i.e. several seconds [7], can result in generator disconnection and ultimately trigger a cascading sequence that culminates in a widespread blackout.

Residential areas are particularly vulnerable to FIDVR as most single-phase induction motors are found in residential air conditioning units. Notably, during the 2024 Balkan blackout, a significant portion of the load consisted of single-phase induction motors installed in air conditioning units, which played a key role in driving the voltage collapse [1].

To study FIDVR phenomena, the Western Electricity Coordinating Council (WECC) has developed a dynamic load representation referred to as the Composite Load Model (CMLD) [12]. This model aggregates various load components, including three-phase and single-phase induction motors, as well as static and electronic loads. Most elements of the load model are equipped with Under Voltage Load Shedding (UVLS) relays. Crucially, in accordance with real-world conditions, only a small fraction of single-phase induction motors in the model are equipped with UVLS relays. This limited deployment contributes significantly to the emergence of FIDVR events. Specifically, these motors remain connected even under low-voltage conditions, and their continued operation in a stalled state leads to increased reactive power demand, thereby hindering voltage recovery. Besides, the model accounts for thermal protection of single-phase induction motors, which disconnects them when internal temperatures exceed acceptable levels. However, this disconnection is delayed as the motors are already stalled and therefore it is insufficient to mitigate the effects of FIDVR in a timely manner.

III. The Swiss Transmission System

This section describes the proposed modeling framework and procedures used to evaluate voltage stability in the Swiss transmission system. First, the development of the dynamic model is described, including generator dynamics and their controls and voltage-dependency of loads. Subsequently, the proposed toolbox integrating long-term and short-term voltage

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stability considerations is presented. Although the Swiss transmission system is of main interest in this work, the method is applicable to other systems.

A. Dynamic Model

To assess short- and long-term voltage stability phenomena, a dynamic model of the Swiss transmission system is needed. The model is derived from static grid snapshots, which isolate the Swiss power grid from larger Continental European models across various planning horizons, such as Day-ahead Congestion Forecasting (DACF) and Intraday Congestion Forecasting (IDCF). As the static snapshots cover only the Swiss system, each Swiss cross-border transmission line terminates at a PQ bus, where load demand is assigned based on the scheduled power exchange at that interface with a neighboring TSO.

Dynamic models for the synchronous machines in the Swiss power grid with Automatic Voltage Regulator (AVR) and Power System Stabilizer (PSS) control models are implemented. Specifically, 113 of the 207 Swiss synchronous machines are assigned detailed generator model parameters, i.e. inertia constant, time constants, and reactances, and an additional 20 machines include AVR and PSS models with accurate parameters. All Swiss hydropower plants with a detailed set of dynamic parameters are assigned PSS/E's GENSAE model, which represents fifth-order salient-pole synchronous machines, while the Swiss nuclear and gas-fired units are modeled using the GENROE and GENROU models, which represent sixth-order round-rotor synchronous machines [13]. The AVRs implemented correspond to standard PSS/E excitation system models, namely ST5C, AC9C, AC11C, AC6C2, and ST8C, while the associated PSS blocks are of type PSS2A, PSS2B, or PSS2C [13]. For the remaining machines that lack detailed information, ENTSO-E's default set of dynamic parameters for the generator model of Swiss hydropower plants is used [14], without additional AVR and PSS control blocks. In addition to the 20 detailed AVR and PSS control blocks, 20 Over Excitation Limiter (OEL) blocks are assigned to the machines with available parameters. For all 20 machines, the chosen PSS/E's OEL model is MAXEX2, which allows the implementation of limiters that follow inverse-time characteristics [13]. OELs are not implemented for machines whose rated and air gap field current information is not available.

Regarding load models, all connected loads are modeled as voltage-dependent loads:

$$P_i = P_{0,i}\left(\frac{V_i}{V_{0,i}}\right) \quad (7)$$

$$Q_i = Q_{0,i}\left(\frac{V_i}{V_{0,i}}\right)^2 \quad (8)$$

where $V_{0,i}$ denotes the initial voltage magnitude at bus i, and $P_{0,i}$ and $Q_{0,i}$ are the initial active and reactive power consumptions at bus i.

The static grid snapshots provide the initial steady-state operating point for dynamic simulations. In particular, the power setpoints of generators included in the snapshots define the operating point of each synchronous machine, while the active and reactive power values at each load bus are taken directly from the snapshots and used as the nominal consumption levels in the load model. Thus, the dynamic model fully leverages all information currently available to Swissgrid, enabling realistic simulations that combine accurate system dispatch and topology with the complete set of known machine-specific dynamic parameters.

B. Proposed Toolbox for Voltage Stability Assessment

Table I presents the proposed guidelines for assessing long- and short-term voltage stability in the Swiss transmission system.

1) Long-term Voltage Stability: As already mentioned in Section II, areas with the highest power demand are the most prone to long-term voltage instability during extreme load growth or uncontrolled load restoration triggered by automatic Load Tap Changer (LTC) actions. Hence, to deploy long-term voltage instability indices such as NLI and RLI [2], [3] in the Swiss transmission system, heavily loaded nodes need to be identified and grouped into areas. For this purpose, geospatial information is used and a statistical analysis of historical load consumption data is conducted.

Load nodes are grouped into load areas based on purely geospatial criteria, aggregating nodes in close proximity and typically radially interconnected. Besides, hourly active power consumption profiles for industrial, commercial, and residential load nodes in the Swiss system are extracted from monthly historical grid snapshots provided by Swissgrid. Load buses that consistently have high consumption patterns across different months are identified as the heavily loaded nodes. The corresponding boundary buses, defined as the entry points of active power into the load area, are then identified. These boundary buses represent the appropriate locations for PMU installation, as they enable measurement of imported active power and apparent conductance, which are required to compute the voltage stability indices.

2) Short-term Voltage Stability: For assessing short-term voltage instability, the CMLD model is assigned to load nodes in densely populated areas, where single-phase induction motors are most prevalent. The dynamic parameters of the model are specified as in [12]. The fraction of single-phase induction motors in the Swiss system is based on statistics on the penetration of air conditioning units in Swiss households [15]. Short-term voltage instability is detected by evaluating post-fault voltage recovery with respect to a Transient Voltage Criterion (TVC) [16], which requires the voltage magnitude to recover close to its nominal value within a specified time period following the disturbance.

IV. Numerical Results

A. Long-term Voltage Stability Results in the Swiss System

To evaluate long-term voltage instability based on NLI and RLI indices in the Swiss transmission grid, extensive dynamic simulations are performed following the procedure described in Section III-B. In particular, a gradual increase in the active and reactive power demand by 1% every 5 seconds for each

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TABLE I
VOLTAGE STABILITY ASSESSMENT
OF THE SWISS TRANSMISSION SYSTEM

Long-term Voltage Stability (NLI, RLI Indices)
1. Identify heavily loaded nodes from historical grid snapshots.
2. Group representative nodes into load areas using geospatial proximity.
3. Identify PMU locations at boundary buses as entry points of active power.
4. Simulate voltage collapse by gradually increasing load demand.
5. Compute NLI and RLI at boundary buses to monitor voltage instability.
Short-term Voltage Stability (FIDVR Analysis)
1. Assign the CMLD model to load nodes in densely populated areas.
2. Apply symmetrical faults at representative load nodes to induce single-phase induction motor stalling.
3. Evaluate post-fault voltage recovery and flag delayed response if TVC is violated.

identified load area of the system is applied until voltage collapse occurs.

Fig. 1 illustrates the evolution of the active power, the apparent conductance, and the corresponding voltage magnitude at the boundary bus of the Zurich load area, which is one of the largest load areas, when the load increase occurs within this area. It can be observed that under voltage-stable conditions, the PMU reports an increase in the apparent conductance, reflecting the local load increase, which is accompanied by an increase in the transmitted active power. However, as the system becomes progressively stressed, the voltage decline triggers a drop in the transmitted active power due to the response of voltage-dependent demand. The onset of this decline is annotated with a dashed vertical line. Simultaneously, the apparent conductance begins to increase more rapidly, resulting in a combination of trends that indicate the onset of long-term voltage instability.

To compute the PMU-based indices, long-term differences of active power and apparent conductance are computed over a 7-second window to filter out short-term transients. For the RLI, only samples exhibiting relative conductance changes $\Delta G_{ki}(t)/G_{ki}(t-\Delta T)$ greater than a corresponding threshold ϵ are retained, with distinct threshold values for each branch. Similar steps are followed to compute the NLI at the corresponding substation. Finally, a 10-sample moving average is applied to the indices to smoothen short-term fluctuations and prevent spurious zero crossings. As shown in Fig. 2, both the NLI, representing the aggregate behavior of all boundary branches of the monitored substation, and the RLIs, computed for each individual boundary branch, experience a zero crossing, signaling an imminent voltage collapse at a time instant where the voltage magnitude is still in acceptable ranges (above 0.95 p.u.). This leaves enough time for automated remedial actions.

B. Validation with Actual PMU Data

To validate the proposed toolbox with field measurements, actual PMU data from a cross-border substation located in northwestern Switzerland are used to compute the RLI index. PMU data of the active power flow on a 380 kV line connecting the Swiss grid to the neighboring French transmission system and of the local voltage at the corresponding substation are obtained with a resolution of one second over a 72-hour period. Since the RLI is evaluated only during periods of increasing apparent conductance, the dataset is filtered to retain timestamps corresponding to power import toward the Swiss system through the monitored interconnection.

Subsequently, to identify typical load variations, filtering thresholds for the RLI are derived. Considering the 7-second evaluation window of the index, a representative load change is defined as an increase in transmitted active power exceeding 5 MW within 7 seconds. The analysis shows that 90% of the conductance changes $\Delta G_{ki}(t)/G_{ki}(t-\Delta T)$ resulting in these

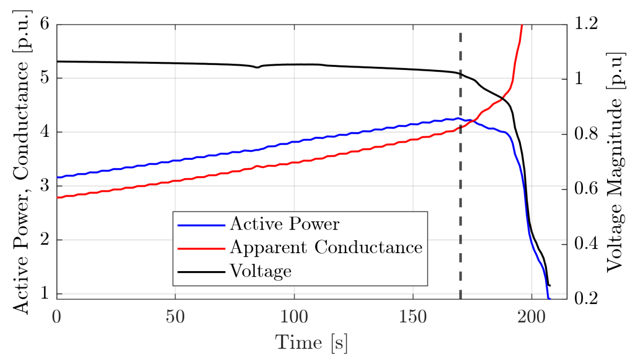

Fig. 1. Evolution of active power, apparent conductance, and voltage in the Zurich load area.

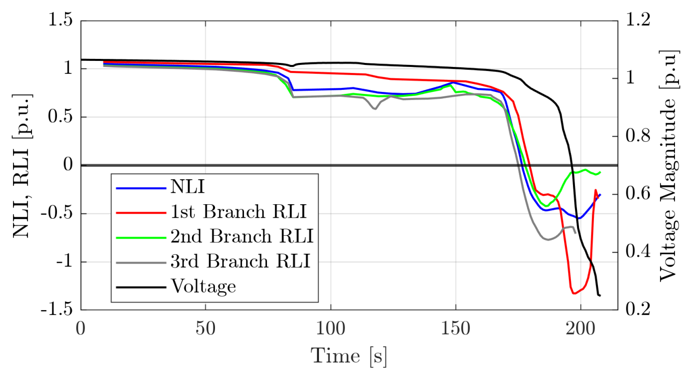

Fig. 2. Evolution of NLI and RLI indices in the Zurich load area.

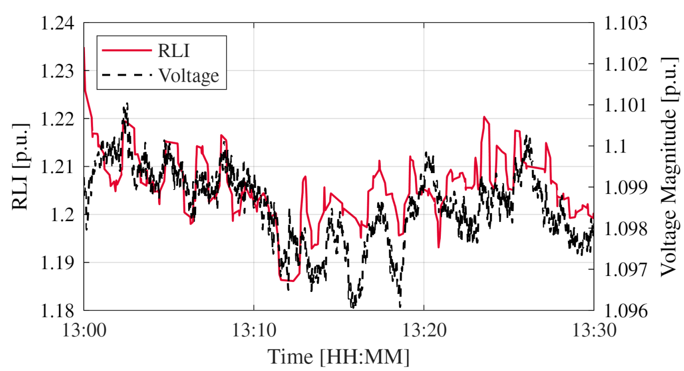

Fig. 3. RLI response using actual PMU data.

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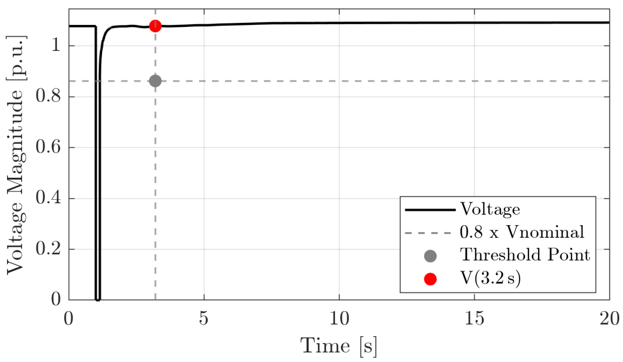

Fig. 4. Voltage magnitude at the boundary bus of the Zurich Area.

situations exceeded 0.0159 p.u. The threshold ϵ is therefore selected as 0.0518 p.u., providing the best balance between smoothness and sensitivity for the index.

Fig. 3 illustrates the response of the RLI under the selected threshold during normal operating conditions. As observed, the index closely follows variations in the voltage profile, providing a meaningful and stable indication of voltage stability without being influenced by transient or extreme fluctuations.

C. Short-term Voltage Stability Results in the Swiss System

Short-term voltage stability is assessed using the CMLD model assigned to load nodes in densely populated areas of the Swiss system. The simulations are performed following the procedure described in Section III-B, using grid snapshots corresponding to the period from January 31 to February 6, 2025. A solid, symmetrical three-phase fault is applied at the studied load node at $t = 1$ s, which is cleared after 0.2 s. Motor stalling is observed due to the disturbance. An integration time step of 0.001 s is used to ensure numerical convergence after fault clearance.

Fig. 4 illustrates the post-fault voltage recovery in the Zurich load area. V_{nominal} represents the pre-fault nominal voltage, whereas the red marker, annotated as V, indicates the instantaneous voltage magnitude evaluated 2 s after fault clearance, namely at $t = 3.2$ s, consistent with the employed TVC [16]. Given the modest share of single-phase induction motors, the voltage recovers rapidly after fault clearance, indicating no violation of the prescribed TVC. Similar behavior is observed in the representative dynamic responses of other load areas, indicating the robustness of the Swiss transmission system against short-term voltage instability.

V. Conclusion

This paper presents a comprehensive toolbox for voltage stability assessment tailored to the Swiss transmission system. A new dynamic model is derived based on operational grid snapshots, enriched with all available generator and load dynamic parameters, enabling realistic simulations. The toolbox integrates PMU-based long-term voltage stability monitoring through the NLI and RLI indices along with short-term stability analysis based on the CMLD representation of load dynamics. Numerical results with dynamic simulations and actual data demonstrate that early warning signals ahead of voltage collapse can be consistently provided. Regarding short-term voltage stability, simulations conducted with realistic single-phase induction motor penetration levels revealed no evidence of FIDVR in the analyzed load areas, indicating that the current residential load composition in Switzerland does not pose a significant short-term voltage recovery risk under typical operating conditions. Future work will focus on enhancing the dynamic model by incorporating the dynamic parameters of additional control blocks.

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