Normalised Voltage Instability Sensitivity Index: A New Concept for Monitoring Voltage Stability in the Control Centre

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SUMMARY

The increasing penetration of power electronics interfaced generation causes among others a displacement of conventional generation. Conventional generation has an inherent voltage control capability and therefore, these capabilities at the disposal of Transmission System Operators are decreasing. A survey conducted by members of the MIGRATE consortium indeed shows that Transmission System Operators expect voltage stability to be of increased concern for securely operating the power system. It is therefore crucial that control room operators are able to efficiently monitor the voltage stability of their power system, as well as get insights on how changes in load or generation influences the voltage stability.

In this work, a new concept for monitoring the voltage stability is proposed. This concept includes a new index, the Normalized Voltage Instability Sensitivity Index N-VISI, and is able to effectively illustrate the impact of generation and load developments on the voltage stability in operational timeframes. Especially the way how different penetration levels of power electronics interfaced generation influence the small disturbance voltage stability can be effectively addressed and visualised. Following the illustration of this new index, high-level guidelines for implementing the N-VISI in the control centre are provided.

KEYWORDS

Small-disturbance voltage stability, power electronics interfaced generation, MIGRATE

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INTRODUCTION

The worldwide energy landscape is undergoing a transition towards a more sustainable power system. As a result of this transition, a rapid technological change is taking place from traditional conventional generation to more and more power electronics interfaced generation (PEIG). This energy landscape will require new tools to assess and new methods to operate the future power system. To address some of these requirements, the MIGRATE [1] project was initiated.

MIGRATE is an European Union funded project under the framework of Horizon 2020 research and innovation programme and stands for *Massive InteGRATion of power Electronic devices*. The overarching goal of the project is to develop and validate innovative, technology-based solutions in view of managing the pan-European electricity system, which is experiencing a proliferation of power electronics interfaced devices (PEIDs), i.e. power electronics interfaced generation (PEIG), power electronics interfaced load (PEIL), and HVDC. As part of the project, a survey was conducted to which more than 20 European transmission system operators (TSOs) responded. The aim was to identify and prioritize foreseen power system stability challenges resulting from increasing levels of PEID in the power system. The TSOs identified challenges related to rotor angle stability (two), frequency stability (three), voltage stability (five), and power electronics interactions and resonances (two), as is shown in Figure 1 [2], [3].
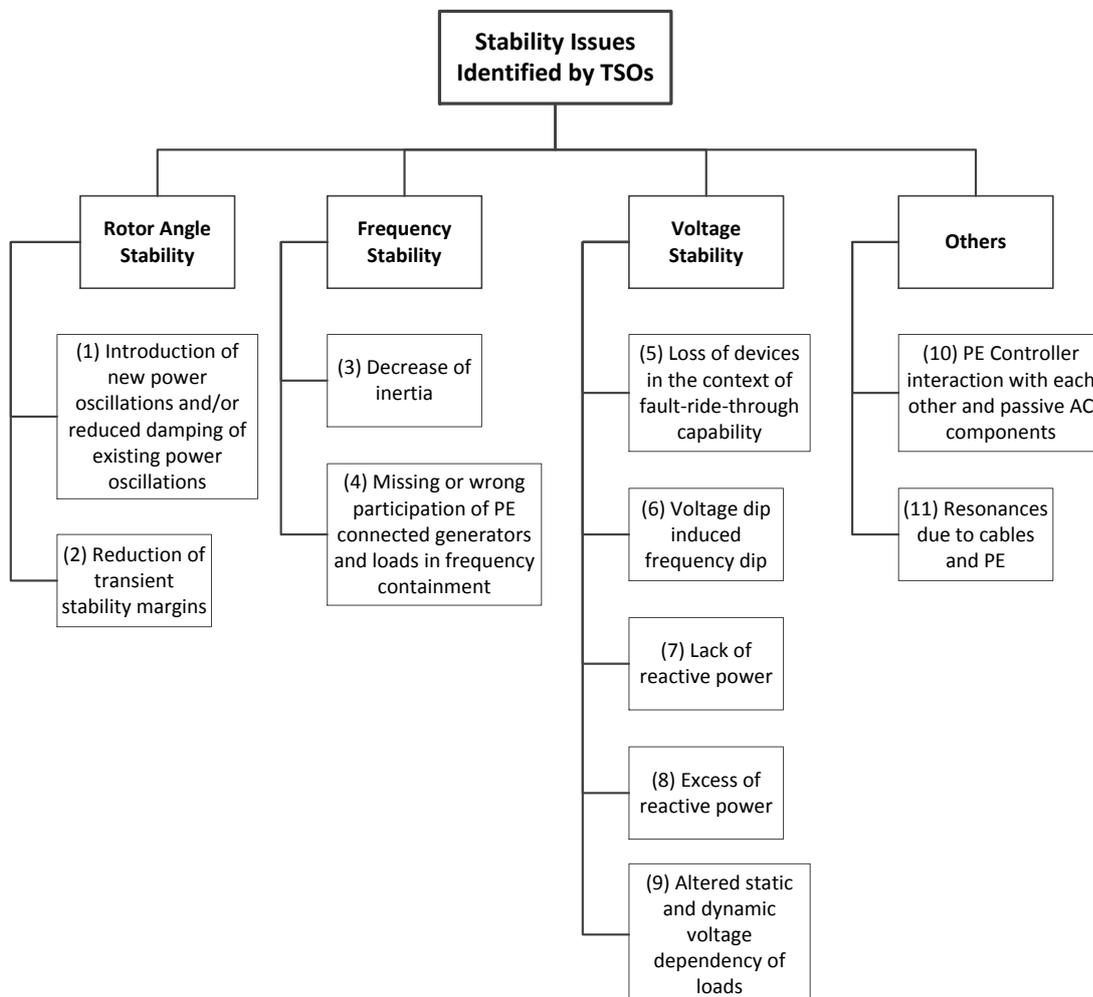

Figure 1 Power System Stability Issues as identified by TSOs [2]

With the increasing levels of PEIG in the power system, conventional synchronous machines are being displaced, resulting in reduced voltage control capabilities. One of the topics identified by TSOs as a potential issue in the future is the lack of reactive power due to increasing penetration of PEIG. Voltage instability appears mostly as a progressive drop of voltages. This can be initiated by either a

short-term, large disturbance event (e.g. short circuit) or a long-term, small-disturbance event (gradual load increase). Most events leading to voltage instability are long-term in nature (in contrast to e.g. frequency stability).

Small-disturbance voltage stability is defined as the ability of any power system to maintain steady voltages when subjected to small perturbations such as incremental changes in system load [4]. In [5] an overview of voltage stability indices is given, whereas [6] presents a comparison of voltage stability indices. Whereas these indices are effective for offline analysis, one of the shortcomings is that they are poor in monitoring the voltage stability in the control centre environment. With the view of monitoring long-term, small-disturbance voltage stability in such environments, a new indicator for small-disturbance voltage stability is developed in this work. The following design criteria are imposed on the new indicator:
- The indicator should evaluate and visually depict the impact of increasing levels of renewables on the voltage stability in operational time frames;
- The indicator or its calculation process should preferably identify weak areas in the system in order to carry out further analysis on specific buses;
- The indicator should give insight in the distance to instability;
- The indicator should be relatively easy to implement in the control room environment.

The proposed voltage stability index in this work makes use of the V/V0 and PV Curve methodologies, which are briefly explained next.

V/V0
The V/V0 index [6], [7] is a rather simple index that determines the weakest bus in a power system. It is the ratio between the actual bus voltage 'V' and a reference voltage 'V0'. The actual bus voltage 'V' is known from power flow studies (offline) or state estimation (online). 'V0' is the voltage at the same bus when all loads are set to zero. This voltage can be obtained using a single offline power flow simulation. The ratio V/V0 gives a voltage stability index. The value can be between 1 and 0 and the lower the index, the weaker that specific bus is[1].

The V/V0 indices across the buses create a voltage stability map of the power system, allowing for immediate detection of weak nodes. Detection of weak areas in the system is beneficial and even more for larger systems. Another advantage of this index is that it has practically no computational burden on the system, and can therefore be carried out more frequently (e.g. for load increases, redispatch, topology changes, etc.). This index is used since 1995 for online voltage stability monitoring (i.e. identification of weak buses) [8].

PV Curve
The Power-Voltage characteristic at buses, also known as PV curves, is a popular method especially in the industry for determining the small-disturbance voltage stability of power systems and is explained in [5]. The major strengths of the PV curve are its robustness, computational efficiency, and easy implementation as a control room application. The shortcomings are in the fact that the PV curve assumes a constant load angle (with increasing loads). Furthermore, it also does not directly give information on the 'speed' to instability, especially with increasing levels of power electronics to load (PE2L) ratios (see next Section). And lastly, the divergence of the power flow does not necessarily match up with the nose point of the PV curve. Whereas for smaller systems, the power flow divergence point and the actual instability point are rather close, the discrepancies can be larger in bigger systems.

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[1]The results from the V/V0 analysis have been validated using Short Circuit Capacity (SCC) calculations for the simulation case. In more than 80% of the simulated cases, the V/V0 method correctly identified the 3 worst buses of the system.

The voltage index that is proposed in this chapter aims at keeping the strengths of the PV curve while addressing the shortcomings. The proposed procedure will also identify the weak buses in a system, so that these buses can be targeted for further analysis.

NORMALISED VOLTAGE INSTABILITY SENSITIVITY INDEX: N-VISI

The Normalised Voltage Instability Sensitivity Index (N-VISI) is proposed as a new indicator for assessing small-disturbance voltage stability. As a first step the V/V0 analysis and SCC calculations are carried out. The V/V0 index gives the weakest bus (or set of weakest buses) in the power system. For this identified bus, a set of power flow simulations are carried out while increasing the load uniformly across the system, until divergence of the power flow solution occurs. For every power flow solution, the changes in voltage and load are recorded for data processing. These steps are repeated for a defined set of weak buses. These steps are automated using Python.

To take into account different penetration levels of PEIG, the index 'PE to load' ratio (PE2L) is proposed and is defined as the part of the load (i.e. the demand in the system excluding AC imports, AC exports, and DC exports) that is covered by PEIG. The mathematical expression for PE2L is:

$$PE2L = \frac{\sum P_{wind} + \sum P_{DC,import}}{P_{load,system}} \tag{1}$$

where:
$\sum P_{wind}$ = total wind generation
$\sum P_{DC,import}$ = total imports from HVDC interconnections
$P_{load,system}$ = load of the system (excluding exports and AC imports)

A value larger than 1 implies that the infeed from PEIG is larger than the load and that the remaining energy is exported.

Fout! Verwijzingsbron niet gevonden. illustrates the data processing steps that are required to calculate the N-VISI.
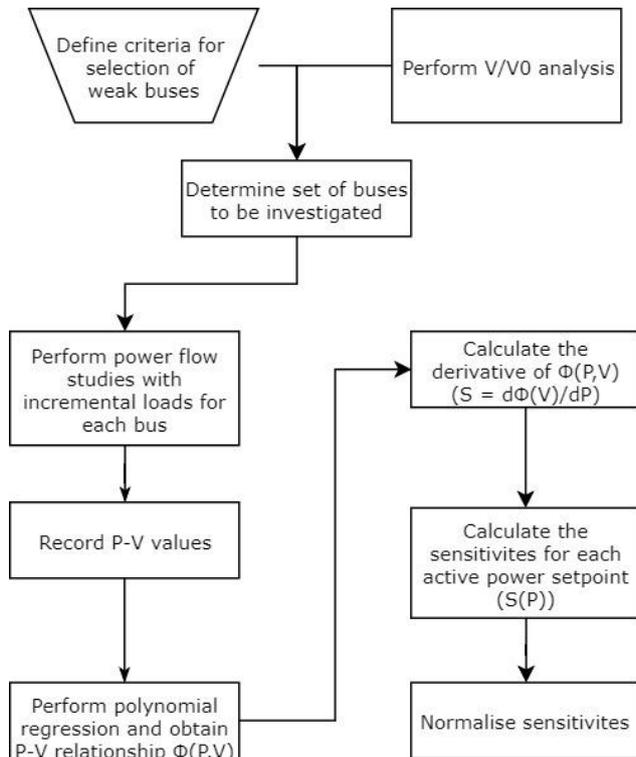

Figure 2 Steps for N-VISI Calculations

Once the loads and corresponding voltages are recorded for the set of identified weak buses (using the V/V0 analysis), curve fitting is applied to obtain a mathematical function for the P-V relationship. As this relationship is non-linear, polynomial regression has been used for curve fitting. The first derivative of the polynomial is then calculated and represents the 'speed' towards the saddle-node bifurcation point (i.e. instability point). For each of the load levels defined in the previous step, the derivative (i.e. the sensitivity) is calculated. As these sensitivities have a wide range for different cases, they are normalised for comparison purposes. Therefore, N-VISI can have a value between 0 and 1: the higher the index, the faster the nose point is reached and the less stable the system becomes.

IMPLEMENTATION OF CONCEPT

The processes described in the previous section have been implemented in the IEEE 9 bus system. The system consists of 3 synchronous generators with IEEE type 1 exciters, 6 transmission lines, and 3 constant impedance loads. The single line diagram is given in Figure 3. The small size of the model makes it particularly suitable for investigating the voltage stability, as the physical nature of observed changes can be relatively easily assessed and explained.

The power system is modelled in DIgSILENT PowerFactory and steady state analysis is used for the assessment of small-disturbance voltage stability. The small-disturbance voltage stability relates to issue 7 in Figure 1 (i.e. Lack of Reactive Power). The concern is that increasing demand in the power system will increase the reactive power needs and displacement of conventional generation by PEIG might result in a lack of reactive power provision.
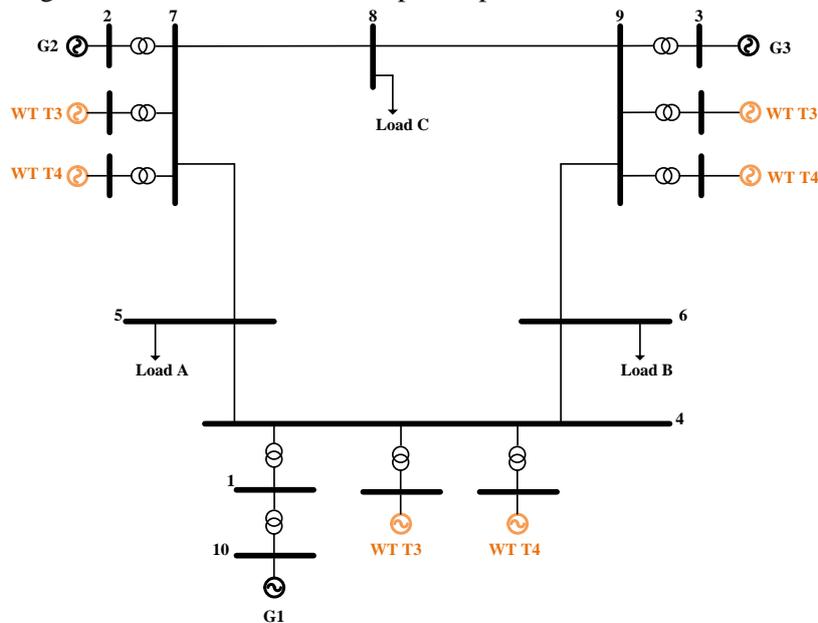

Figure 3 Modified IEEE 9 Bus System – Single Line Diagram

In order to assess the influence of increasing levels of PEIG on the small-disturbance voltage stability, the IEEE 9 bus system is modified to include wind turbine generators type 3 and type 4 at buses 4, 7, and 9 (marked in orange). Another implemented modification is the use of 10 parallel machines for generators G2 and G3. The machine ratings are changed to 1/10th of their initial values. To assess the impact of small-disturbance voltage stability, the parallel generators at bus 2 are switched off one by one. The PEIG is increased with the same amount. After all parallel machines at bus 2 are switched off, the number of parallel machines at bus 3 are decreased in steps.

The V/V0 analysis was performed on this system and bus 5 was identified as the weakest bus. For different PE2L levels the, PV curves and the N-VISI are calculated for bus 5 and are presented in Figure 4. It should be noted that the N-VISI does not represent any physical variable of the power system, as is the case with other voltage stability indicators [9]. It is rather a normalized metric

between 0 and 1, where 1 represents an instable system. The coloured lines in the figure are iso-PE2L ratio lines (i.e. operating points across lines with the same colour have the same PE2L ratio). It can immediately be observed that the N-VISI index is more effective in terms of illustrating the impact of increasing levels of PE2L levels. It shows already from the initial loading of the system (315 MW) how stable it is in terms of different PE2L levels, something which is difficult to assess using the PV curves (voltage collapse can occur at voltage magnitude close to 1 p.u.). For each loading level the distance to instability can be read from the N-VISI curves.
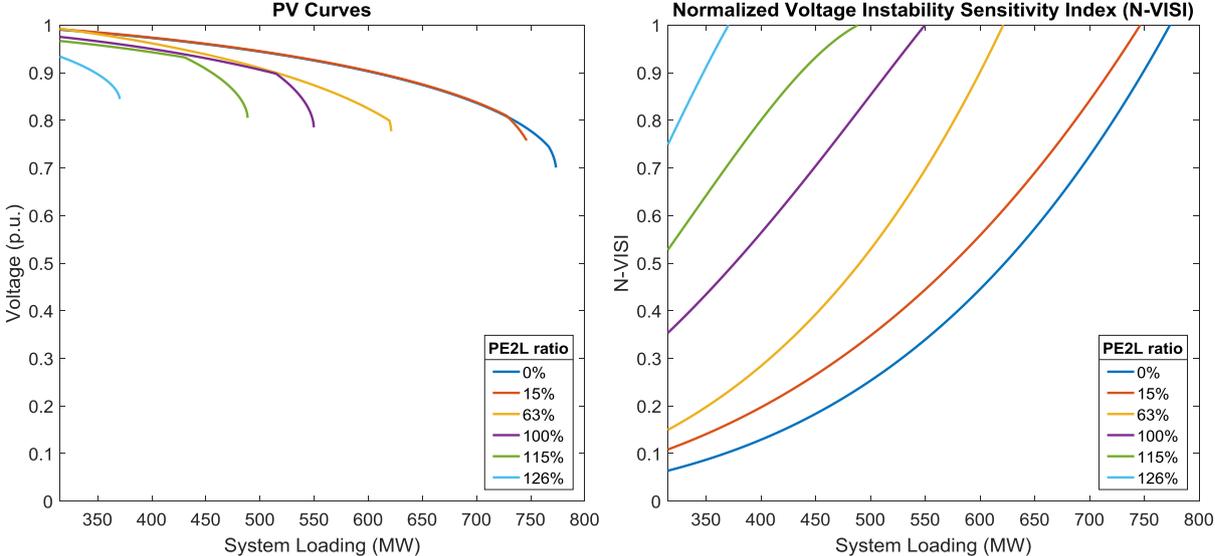

Figure 4 PV and N-VISI Curves for Bus 5

The impact of changing operating conditions on the voltage stability is shown in Figure 5. Starting at operating point A, an indication of how stable the system is compared to other operating conditions (increase in loading or PE2L ratio) can be perceived. Operating point A represents an initial operating state with a certain load and 0% PEIG (PE2L ratio is 0). Compared to operating point A, the load in operating point B is increased, whereas the PE2L ratio is still 0%. When the operating point changes from A to B, the effect of the load increase is observed by moving along the blue trajectory.

The load in operating point C is identical to operating point A, whereas the PE2L ratio now is increased to 100%. When the operating point changes from A to C, this symbolises an increase in the PE2L ratio. The effect of this change on the voltage stability is observed by moving from the blue line to the purple line. In operating point D the load as well as the PE2L ratio is changed.
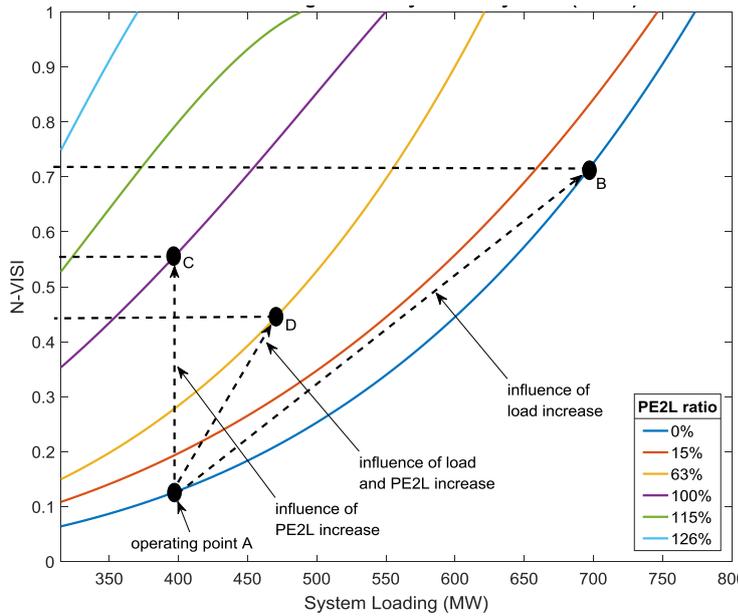
Figure 5 N-VISI Curves for Bus 5

As can be seen from the results of the N-VISI, this new indicator not only gives insight into the distance to instability, but also illustrates effectively the impact of system changes (PE2L ratio and load) on the voltage stability. As the N-VISI uses the complete set of data of each PV curve, the faster decrease of the N-VISI for the yellow line (63% PE2L ratio) compared to the 0% PE2L ratio, and the earlier collapse of the purple line (100% PE2L ratio), also compared to the 0% PE2L ratio can already be observed by the higher N-VISI at initial loading conditions.

CONTROL CENTRE IMPLEMENTATION

The concept of the N-VISI index developed in this work can be implemented in the control room. For each step in the calculation process the requirements are presented. The V/V0 analysis requires two inputs. The actual bus voltages 'V' can be retrieved from the SCADA. For calculating the zero-load voltages 'V0', the actual grid topology is required, which can also be retrieved from the SCADA. A steady state power flow program is required to calculate the V0 voltages, after which the V/V0 analysis can be conducted. Next, a set of weak buses is selected based on the V/V0 indices and for each bus N-VISI curves are calculated for different levels of PE2L ratios. It should be mentioned that the criteria for selecting the set of weak buses can be different across different jurisdictions and depends among others on the risk appetite of the system operator. However, the approach presented in this work can easily be extended to all buses, instead of only a subset.

The steady state power flow program can be used to simulate the P-V characteristics at each of the identified buses and for each of the PE2L ratios. The PE2L ratios can be defined based on the operational planning schedules (network topology, dispatched generation, exports, and imports) which are known in advance. In order to calculate the N-VISIs, a software capable of doing the defined mathematical operations (polynomial regression and derivative calculation) is required. Once the N-VISIs are calculated, a visualisation tool is needed to illustrate the current operating point on the iso-PE2L lines of the "N-VISI vs Load" graphs.

However, for implementing the proposed voltage stability index for real time operations, there are two main challenges:
1. Determining the PE2L ratio in real time is practically impossible at this moment. The reason for this is that the transmission system operator can only observe the vertical load (i.e. load at the transformer between TSO and DSO, where installed PEIG on DSO level is subtracted from the actual, real demand).
2. As the power system in reality is in quasi steady state, control room engineers need to define triggers based on their operational experience (e.g. minimum observed change in load) for re-running the N-VISI calculations.

CONCLUSIONS

The aim of this work was to develop a new index for voltage stability. The Normalised Voltage Instability Sensitivity Index was developed and proposed. This index has two major advantages. Firstly, it provides information on the distance to instability in terms of sensitivities. Secondly, the influence of changes in the load and/or power electronics interfaced generation on the voltage stability can be illustrated in a comprehensive manner for the control room operator. The process for calculating the N-VISI defines the weak buses in the system by using the V/V0 analysis. Using the V/V0 method for each iteration can illustrate how the set of weak buses in the power system shifts as a result of specific control actions. Furthermore, two disadvantages have been observed with the N-VISI. Firstly, the load increase in the implemented concept is modelled based on a uniform load increase across all the load buses. A new operating point based on an asymmetrical load increase would require carrying out new analyses. Secondly, the index is situation specific: changes in the network topology, dispatch or loading will require new calculations. However, as the required calculations are based on steady state simulations, which can be performed fast, this is not expected to be of major concern.

ACKNOWLEDGEMENT

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