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Fundamental study on the influence of dynamic load and distributed energy resources on power system short-term voltage stability

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ABSTRACT

The number of Distributed Energy Resources (DER) and dynamic loads is increasing rapidly in modern power systems. Their aggregated effects on power grid dynamics are, however, still insufficiently explored. It is expected that distribution-transmission interactions will be more pronounced in the future, resulting in a stronger need to analyse such effects. One of the emerging issues in modern systems' distribution-transmission interactions is short-term voltage stability (STVS), which at present receives relatively low attention among the researchers. This paper utilizes advanced load and DER models in a large-system study, intending to determine the relationship between various distribution system specifics and the bulk power system STVS. Based on a developed heuristic method that generates a big data set by performing an extensive number of simulations, it is shown how the dynamic load and DER interact with each other in terms of STVS, and what load and DER amounts and types are beneficial or detrimental to modern systems. The study improves the understanding of modern distribution-transmission interactions related to STVS and emphasizes the importance of more accurate future modelling and analyses.

1. Introduction

One of the key strategies in addressing climate change is the shift to more sustainable sources of energy. Electricity generation plays a major role in this, as electrification takes place in most of the energy sectors [1]. We witness renewable energy sources (RES) emerging in the majority of modern grids. While some sources such as large solar or wind farms are usually connected directly to the transmission system, a vast amount of renewable energy production is scattered on medium and low voltage networks. This results in a rapid energy increase generated from distributed energy resources (DER) [1–2], which is accompanied by the effects on the system dynamics that are often no longer negligible [3–9].

The behaviour of larger RES is well explored as it is feasible and computationally possible to include their models in power system studies; this is, however, not so straightforward with DER. A large number of units scattered both geographically and electrically across a power grid makes the modelling task very challenging. Therefore, the influence of DER on the bulk power system (BPS) is comparatively less explored than the impact of individual large RES, for which accurate models are mostly available. Furthermore, centralized large RES units often have more sophisticated control possibilities than smaller DER units have. This limits the DERs' relative potential to support the voltage during and after disturbances [7–8].

The issue is even more emphasized by the fact that system operators rarely have sufficiently accurate information about the DER units on distribution levels. The exchange of information between distribution system operators (DSOs) and transmission system operators (TSOs) is becoming increasingly important as more interactions between the two systems take place [10]. However, present industry practice shows that most DER modelling is rather simplistic, e.g. aggregation as a negative load, often even for dynamic studies [11].

Except for the increase in DER penetration, the electricity demand is evolving as well. Most of the distribution systems make use of an increased number of complex and/or dynamic loads such as induction motors and electronic loads. At present, the models used for analyses are often still very basic, even for dynamic studies [12–13].

These simplifications often neglect major dynamic interactions occurring in the modern distribution systems, which can significantly affect the bulk power system, as it will be demonstrated in this study.

This paper mainly explores voltage stability issues and it is focused particularly on short-term voltage stability (STVS). While long-term voltage stability has been extensively investigated in the past

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[4,14–17], there is not much research performed on short-term voltage stability [14]. Meanwhile, short-term interactions between dynamic loads, DER, and their low-voltage ride-through (LVRT) criteria have become very complex and increasingly relevant to analyse. Some recent studies address separately dynamic load [18–19], DER [20–21], and LVRT influence on STVS [22–24], but comprehensive research on the mutual interactions and combined effects on bulk power system STVS is still missing.

The research in this area is insufficiently mature, possibly due to a large complexity and many variables. To overcome this issue, this paper utilizes Python scripting in DIgSILENT PowerFactory 2020 SP2 software [25–27]. Such programming interface access to PowerFactory allows user-specific and versatile functionalities. This effectively enables us to evaluate multivariable problems time-efficiently, and to assess better various parameters' influence on the system dynamics. It also provides us with the possibility to use extensive Python libraries to generate, analyse, and present vast amounts of simulation results.

Analysing large data sets enables this study to consider the effects of various changes in load and DER composition on STVS, as well as to consider bulk power system dynamics and various fault scenarios. In comparison to the current research extent in STVS, this approach is therefore much broader and more inclusive.

The main contribution of this paper is to improve the understanding of short-term voltage stability, with the emphasis on dynamic interactions that take place in modern distribution grids, which may propagate throughout the power system. The influence of various dynamic load types and amounts on STVS of the grid is analysed, by providing an improved understanding of their contribution to STVS inception. Furthermore, the study addresses a vastly unexplored influence of DER units on system STVS, in terms of the penetration and control strategy. Finally, the paper highlights the necessity of advanced distribution models' utilization in voltage stability analyses.

The paper is divided into five main sections. The first section, the introduction, presents the research motivation and the current scientific extent. In the second section, the advanced models which are applied in this paper are presented, together with their implementation in the bulk power system model. The third section describes the applied methodology and categorizes short-term voltage instability cases. In the fourth section, the results are presented followed by a comprehensive discussion on relevant findings. Finally, meaningful conclusions are discussed in the fifth section.

2. Advanced system modelling

The obtained results based on simulations are naturally heavily influenced by the accuracy of the models. Whilst available power system models have been so far sufficiently accurate in replicating the system dynamics, recent changes driven by the advances of power electronics and renewable energy generation require a re-evaluation of conventional models. Two types of advanced models are utilized for dynamic load and DER modelling in this study, the WECC Composite Load Model and DER_A model, respectively. The choice of these models relies on various research behind them, which indicates their suitability for replicating modern distribution system dynamics for large system studies. The aforementioned models are highlighted following the next subsections. Finally, these models are incorporated in an IEEE test grid, which is broadly recommended for voltage stability studies. This test grid is utilized to perform a large number of dynamic RMS simulations, with the purpose of exploring the effects of various types of dynamic load and DER units on short-term voltage instability. This section elaborates on the models and the test grid utilized in the analysis.

2.1. Advanced load modelling – WECC composite load model

Load modelling is an important part of power system studies and it has attracted a lot of research attention in the past [28]. It is impractical to model every load accurately, as this will impose two issues. Firstly, the actual inability to do so due to a large amount of uncertainty and data unavailability, and secondly, even if the loads are accurately modelled, the complexity of the whole model would be too large for any practical bulk power system simulations. Hence, a trade-off is found in having enough precision with a limited level of complexity. This is achieved by using aggregated load models, like the WECC Composite Load Model, which is presently one of the best models for such a task. The model is initially developed in 2012 and since then it has been repeatedly updated and validated [29–30]. Fig. 1 shows a schematic structure of the model, including the DER_A model shown in red colour, which is discussed in section 2.2. Its ability to take into account various compositions of the load, allowing more precise dynamic response modelling, makes this model very attractive.

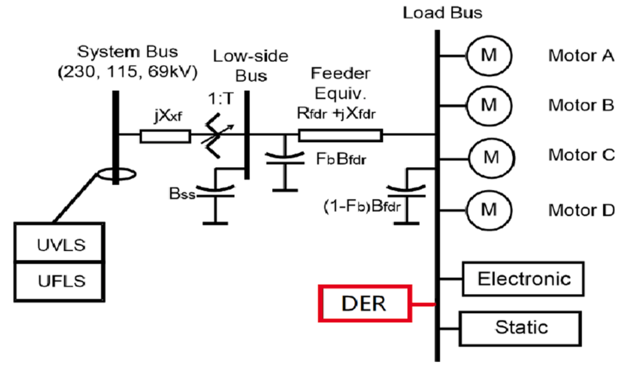

Fig. 1. WECC Composite Load model (incl. DER_A model).

Furthermore, its complexity is kept at a reasonable level, resulting in great interest from both academia and industry. The system contains feeder representation, several types of motors, an electronic load and a static load. More information about this can be found in [29–31]. The share of different load types is adjustable to any particular case or system.

The model that is used in this paper is the WECC Load Model from DIgSILENT PowerFactory 2020 SP2A [32–33]. The analysis utilizes default software values for the WECC Composite Load Model parameters, whilst the share and penetration of each of the motor types are varied throughout the simulations. More information on this can be found in section 4. Additionally, [19,34] provide a more comprehensive analysis in terms of load parameter uncertainty, which is beyond the scope of this paper.

2.2. Advanced DER modelling – DER_A model

Except for the load effects on STVS, a strong impact on modern grids is caused by the integration of distributed generation in distribution grids [4]. Since most of the DERs are coupled with the grid using an inverter, their dynamic behaviour is largely dominated by the control strategy rather than the generation unit specifics.

DERs come in various types, sizes and with several possible control strategies. Furthermore, their distribution all over the network makes them very hard to model and incorporate in analyses. As accurate models are computationally time-consuming and difficult to develop, the use of aggregated models is the viable way to take into account the DER effects in a larger system study.

The most advanced aggregated DER model up to date is the DER_A model [35]. In comparison to its predecessor, the PVD1 model, DER_A has enhanced abilities to represent various control strategies and Low-Voltage Ride-Through (LVRT) operation, while exhibiting a lower overall complexity. The detailed model diagram and further information can be found in [31,35–39].

Additionally, the model can be successfully incorporated with the WECC Composite Load model, shown in red in Fig. 1. The model used in

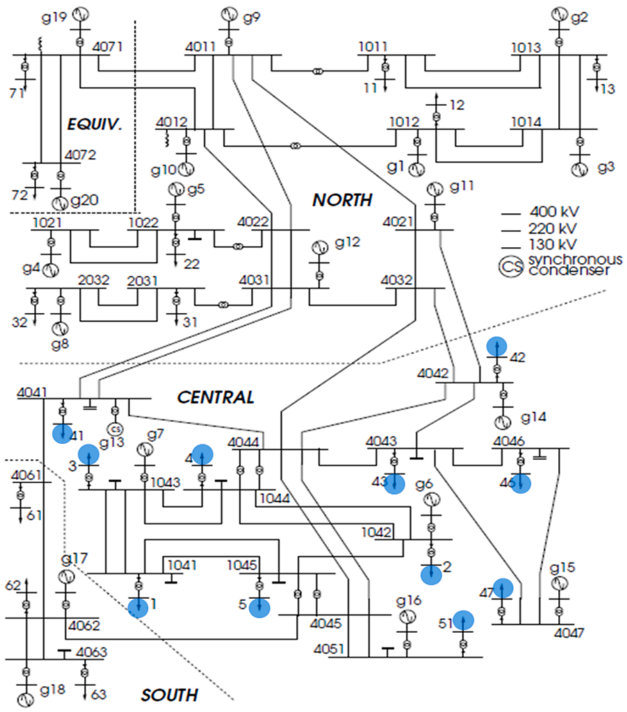

Fig. 2. IEEE Test System for Voltage Stability Analysis and Security Assessment, with blue circles indicating where WECC composite load and DER_A models are implemented.

this study is the DER_A model from DIgSILENT PowerFactory 2020 SP2A, validated in [40]. The parameters of the model are mostly based on their default PowerFactory settings, as these values are validated, while some variables of interest to STVS are varied throughout the analysis. The details on the parameters can be found in the appendix and section 4.

2.3. IEEE test system for voltage stability studies and its adaptations

There are various test grids in academia used for dynamic studies. However, the IEEE Test System for Voltage Stability Analysis and Security Assessment [41] represents the most comprehensive grid for voltage stability studies. The grid model contains all the necessary specifications for a realistic dynamic response representation. Furthermore, the dynamic constraints this system experiences during simulations are precisely in terms of voltage stability [42]. Hence, this model is, at present, extensively used for voltage stability research. More information can be found in [41–43].

The basic system is enhanced for this study by introducing WECC Composite Load models, i.e. replacing static loads in the central area of the system. The reason for choosing this part of the grid lies in the fact that great amount of the load is located in this area, and the dynamics of the area itself are the most prone to trigger voltage instability, as explained in [41–43]. Furthermore, DER units based on the DER_A model are introduced in the central area as well.

This creates conditions to practically analyse the effects and mutual interactions of DER penetration and dynamic load presence on STVS of the bulk power system more accurately than ever before. The system's diagram and the locations where load and DER models are introduced is shown in Fig. 2, while the details of the changes are enlisted in section 4.

WECC Composite Load models and DER _A units are introduced in equal amounts on the central busbars, hence the influence of geographically and electrically heterogeneous penetration in the grid, including the influence of the respective distribution network topology, are not considered in this study. The analysis of such effects was investigated to some extent in [44–45].

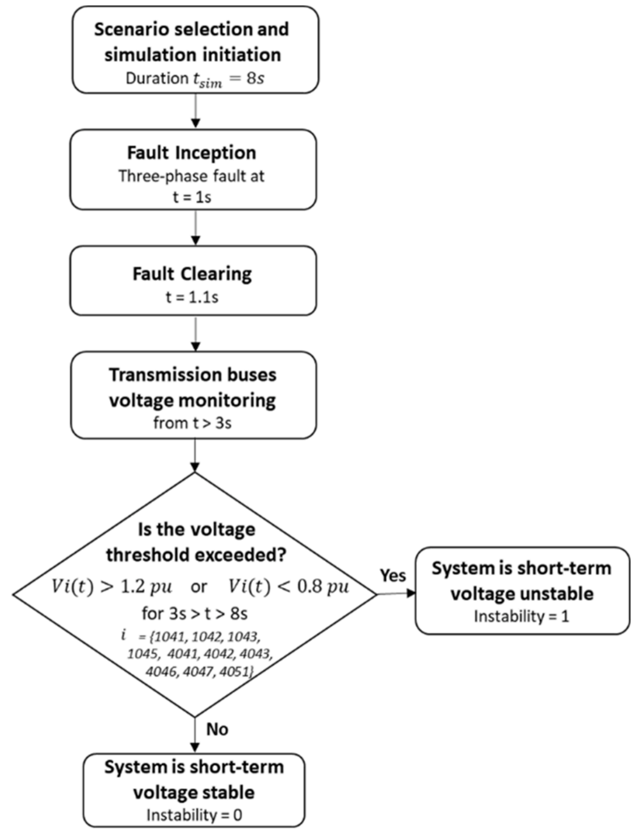

Fig. 3. A flowchart of the methodology for STVS evaluation of transmission buses from the central area of the system in Fig. 2.

3. Methodology for automatized short-term voltage stability evaluation

Short-term Voltage Stability describes voltage variations in the period of several seconds, mainly dictated by fast-acting load components, induction motors, electronically controlled loads, HVDC links and inverter-based generation [46]. In [47], EPRI defines STVS as mainly related to motor stalling, where the phenomenon typically takes less than 15 s. This paper deals with various dynamic load components with the addition of inverter-based generation, while HVDC links and detailed electronically controlled loads' influence are beyond the scope. Furthermore, it is important to mention that STVS is closely related to other short-term dynamic phenomena such as transient rotor angle instability and fault-induced delayed voltage recovery (FIDVR), and even slow converter-driven instability [46]. It is often hard to clearly distinguish between these phenomena, as they emerge in approximately the same time scale and tend to be strongly associated and mutually exciting [21,46].

Although the definition of STVS is clear, finding a precise criterion that defines if a system experiences short-term voltage instability is not so explicit. The general understanding of the instability is that the system is unable to maintain steady voltages after being subjected to a disturbance [46]. However, the exact criterion would depend on the grid in question, its resilience to voltage excursions, as well as the protection system coordination, so that the overall system would not experience a large number of cascading faults that could lead to potential widespread instability. There are not many reliable STVS evaluation methods available, and most of them were not validated for modern power system dynamics. This is another research gap that we plan to address as a future challenge. Therefore, here we propose a straightforward

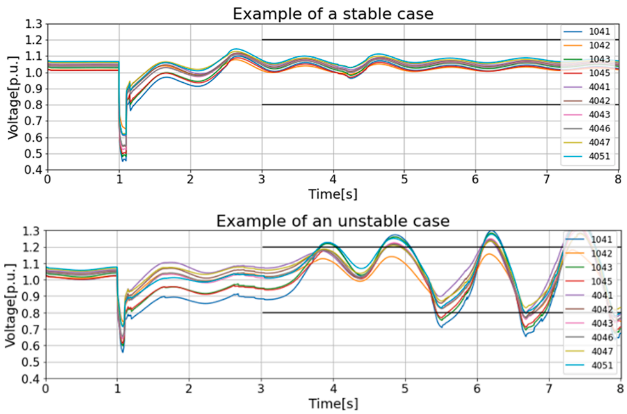

Fig. 4. Examples of the STVS methodology applied in the study. The top figure (a) represents a stable case, and the bottom figure (b) unstable.

evaluation method based on the voltage levels several seconds after a disturbance.

The flowchart in Fig. 3 describes the methodology developed as a basis of the performed analysis in this work. The algorithm begins with the scenario selection and simulation initiation, shortly followed by the fault inception and fault clearing. The scenarios are described in section 4.

Throughout this process, the transmission bus voltages are monitored continuously. Once the voltage values are obtained for the full simulation time (8 s), their values are analysed to check whether they surpassed upper or lower set thresholds (1.2 and 0.8 per unit, respectively). If at least one of the voltage values is outside of the defined thresholds at any moment after 3 s, the system is considered unstable. The value of 3 s is chosen to avoid initial fault-induced voltage variations, which could lead to incorrect categorisation of the results. The buses in vector $\boldsymbol{i}$ selected for analysis are taken as major transmission buses in the central area of the grid, which allows capturing most of the central region dynamics.

To clarify this methodology further, Fig. 4 shows examples of short-term voltage stable and unstable case, respectively.

Black horizontal lines represent the utilized threshold, which should not be surpassed, i.e. all the voltages should stay in the zone in-between the black lines for STVS to be preserved. Fig. 4a shows a case of stable operation, whilst Fig. 4b shows a case where the system is short-term voltage unstable. The short-term instability can be experienced either as a sharp drop in voltages, unsustainably low post-fault voltages, or as undamped voltage oscillations that eventually lead to a voltage collapse. These differences exist due to the mentioned close relation between STVS and other short-term dynamic stability phenomena, such as transient angle rotor stability and fault-induced delayed voltage recovery.

The figures are merely two exemplifying cases of low (4a) and high (4b) amount of dynamic load present in the grid and its influence on STVS. Extensive analysis in this regard will be demonstrated and explained in section 4.1.

It should be noted that these conditions are not ideal and that some events will be incorrectly categorized. These conditions should instead be thought of not as a definite STVS evaluation but as an approximation framework that will allow automatic instability check in Python, with results to be collected and used for creating correlation heatmaps. Failure to fulfil the presented conditions can be also thought of as an imminent threat to short-term voltage stability, i.e. a system being in severe danger of voltage instability. Nevertheless, most of the events will indeed be properly categorised since the majority of grids would not be able to recover from so high or low voltage situations without severe consequences. Hence, with a very large number of simulated cases, the overall conclusions hold. Slight differences for specific systems are, of course, plausible.

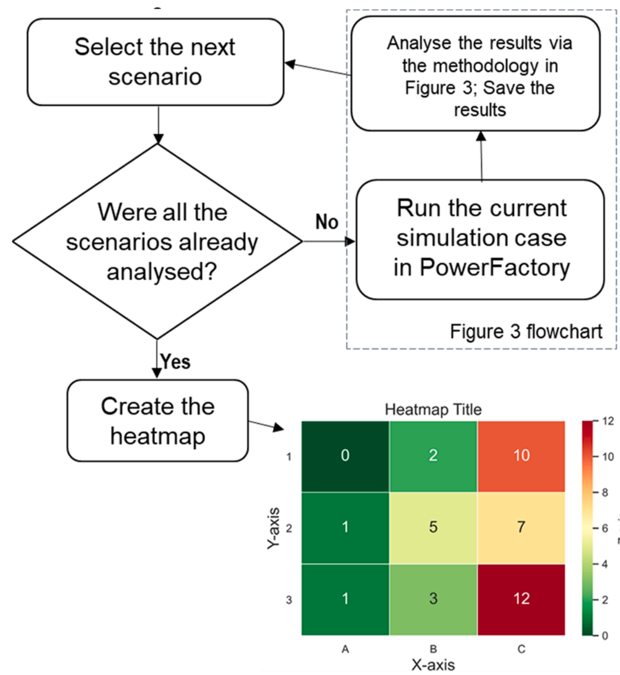

Fig. 5. A flowchart of the entire Python-PowerFactory methodology, with the correlation heatmap example as a result.

This methodology is applied recursively, following a flowchart shown in Fig. 5, conducted in Python 3.8.3 (using Jupyter Notebook) and DIgSILENT PowerFactory 2020 SP2A in parallel.

Fig. 5 describes this recursive Python-PowerFactory process. Firstly, the scenario is selected, after which it is checked whether all the scenarios are already analysed. If that is not the case, the flowchart connects to the algorithm in Fig. 3, and the process repeats itself until all the scenarios are analysed. Once this is completed, the resulting instability data is presented on a heatmap.

The created heatmaps are based on [48] and will be used throughout the paper to visualize the results effectively. Different parameters will be varied on X and Y-axes, while the Z-axis will be used for twelve different short-circuit scenarios in the grid. The locations and the rationale for these fault locations and types are discussed in section 4.

The numbers in the heatmap blocks demonstrate how many of those short-circuit scenarios are unstable, as per the presented methodology in Fig. 3. The numbers are also shown in a coloured box, for clearer visualization, in a colour spectrum from green (low number of instabilities), yellow (medium number of instabilities), to red (high number of instabilities).

This methodology allows analysing automatically a vast number of grid scenarios to derive conclusions on which load and DER specifics of interest are most correlated with the short-term voltage instability, and in what amount do they contribute in its inception or suppression.

All simulations are run on a Windows 10 PC, with Intel Xeon W-2123 3.6 GHz CPU and 8 GB of RAM, resulting in a total simulation time of ~300 h.

4. Results and discussion

The analysis comprises two main directions. The first is the influence of the dynamic load models on STVS without any DER penetration in the grid. The second direction of the analysis follows up on the first one, by introducing DER penetration in the distribution grids as well, to evaluate the overall effects and interactions of dynamic loads and DERs together.

4.1. *Influence of dynamic load modelling on STVS*

The first part of the analysis deals with the influence of the dynamic load on STVS. While it is known that dynamic loads are the main culprits of short-term voltage instability, the amounts of their penetration in the grid that could cause a system-wide instability are less known. Furthermore, how different induction motors in the grid relate to the STVS is unclear as well, since the existing research is mainly of a theoretical type or a case-study type on a smaller system.

Hence, the research questions we are trying to answer are as follows:

1. *What will be the amount of dynamic load in a grid that may cause a significant impact on STVS?*
2. *How does each type of dynamic load affect STVS, and which types are the most dangerous for the bulk power system STVS?*

To give comprehensive answers to these questions, the model presented in section 2.3 is adopted. The default model in its operating point A is taken as a basis, which is described as a voltage stability constrained operation scenario [41]. It is modified and extended by introducing 11 identical WECC Composite Load models to the central region of the system, as shown in Fig. 2. The model parameters are kept at default PowerFactory values, except for the voltage level and base power adaptations to match the IEEE Test system. The share of each load type in the analysis is presented further in the text.

The busbars where the WECC Composite Load models are introduced (replacing static load in the basic model) are listed in the table below.

Furthermore, the same table shows which busbars are used to create twelve different 3-phase short circuit scenarios. The faulty buses are chosen to be dominantly in the central region, as this will likely lead further to voltage instabilities due to two reasons. Firstly, the IEEE system was made to be susceptible to voltage instability in the case of North-Central corridor faults [41,42]. Secondly, due to the addition of dynamic loads and DER units in the central area, it is expected that such nearby faults will aggravate more severe dynamic events. Except for this, a few faults in the proximity to the central area are also analysed, so that a larger variety of faults are taken into account. A three-phase short circuit is chosen, as its severity is more likely to initiate voltage instabilities.

The amount of composite load is varied by replacing the static load, in a range between 0 and 50% of the total system demand, in 5% steps. Cases above 50% are not shown, as such penetrations are not so common in power systems. The steps of 5% are selected as a compromise between desired sensitivity, computational complexity, and results' clarity.

Except for this, 10 different compositions of load are used to evaluate how different types of motors affect STVS. Table 2 summarizes this methodology.

The motors of types A, B, and C are utilized in the model to represent different types of three-phase motors. Model A represents low inertia induction motors driving constant torque load, e.g. compressor motors. Model B represents induction motors with high inertia, driving quadratic torque loads, e.g. ventilation systems. Model C represents low-inertia induction motors driving quadratic torque loads, such as centrifugal pumps. Finally, Model D is a representation of single-phase induction motors, e.g. air conditioning units. More information about the motor types can be found in section 2 and its respective references [e.g. 29–31].

The rest of the dynamic load composition, i.e. 40%, is kept in electronic load (15%) and static load (25%) in all the scenarios, as it is practically highly unlikely to have only induction motors in the demand of a large grid. This should be taken into account when evaluating the absolute total amount of each type of motor in the load.

The presented analysis framework results in 1320 dynamic simulations of 8 s duration each, ran via a Python script connected through DIgSILENT PowerFactory 2020 SP2A. In each simulation, central bus voltages are monitored to determine if the STVS is preserved in terms of the methodology from section 3. An example of such a measurement is already shown in section 3, in Fig. 4. The heatmap resulting from this analysis is shown in Fig. 6.

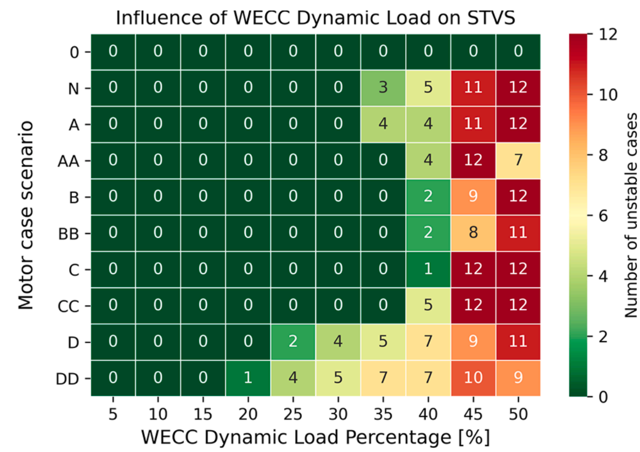

Fig. 6. Correlation heatmap of WECC Dynamic load influence on STVS with a variety of presence and type of dynamic loads.

Table 1
Buses with advanced load models and buses where the fault is simulated (see Fig. 2).

Central region MV buses with advanced distribution models	Transmission buses where the fault is simulated
1	1041
2	1042
3	1043
4	1044
5	1045
41	4031
42	4032
43	4041
46	4042
47	4043
51	4044
-	4062

Table 2
Dynamic load composition scenarios.

Load composition scenario	Description of the scenario	Share of motors (per unit) A/B/C/D
0	Static load	0/0/0/0
N	Equal share	0.15/0.15/0.15/0.15
A	More A-type	0.3/0.1/0.1/0.1
AA	Majority A-type	0.45/0.05/0.05/0.05
B	More B-type	0.1/0.3/0.1/0.1
BB	Majority B-type	0.05/0.45/0.05/0.05
C	More C-type	0.1/0.1/0.3/0.1
CC	Majority C-type	0.05/0.05/0.45/0.05
D	More D-type	0.1/0.1/0.1/0.3
DD	Majority D-type	0.05/0.05/0.05/0.45

The X-axis represents an increasing share of WECC Composite Load models replacing static loads. The Y-axis takes all the scenarios from Table 2 for analysis. Finally, the legend shows the number of unstable scenarios, based on the 12 analysed faults enlisted in the second column of Table 1. As explained in section 3, the numbers in the heatmap blocks represent how many fault cases, out of the total of 12, are short-term voltage unstable for the corresponding parameters on X and Y axes. Larger (smaller) numbers, visualized with the colour spectrum for further clarity, effectively indicate a stronger (weaker) correlation of

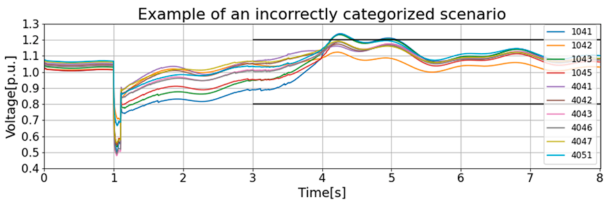

Fig. 7. An example of an "incorrectly" categorized scenario with a high share of D-type motors.

those parameter values with the short-term voltage instability inception.

From the heatmap, it can be seen that the dynamic load percentage below 20% does not affect STVS for any of the given scenarios. With percentages of dynamic load between 20 and 35%, some instability is observed, while for 40–50% most scenarios exhibit an inability to cope with the majority of the faults in terms of STVS. For even higher percentages, which are not shown, we find that most of the cases are unstable. For the sake of comparison, a basic model with only static load is shown in the first row of the heatmap, where all the cases are evaluated to be stable. Clearly, dynamic load plays a large role in short-term voltage instability inception. It should be noted once again that the percentage values are not absolute in terms of static-dynamic load ratio, as explained earlier since even the WECC Composite Load has 25% of the static load in its composition in all of the scenarios.

Hence, in terms of maximum penetration of dynamic load (induction motors), approximately more than 25–30% is predominantly related to instability in the studied grid, with shown differences depending on the type of the motors. This number depends on how constrained is the analysed operating state of a system, with emphasis on the available voltage/reactive power support, fault type/intensity, fault clearing time, power flows/contingencies, and the available Q-reserves and/or emergency control possibilities.

In terms of the second research question, by analysing response for different load compositions, several patters can be seen. Firstly, scenario N with an equal share of dynamic load types (see table 2) begins to show an increasing number of instability scenarios starting from 35% dynamic load share. Moreover, motors A and C, seen from scenarios A/AA/C/CC (see table 2), show worse results in Fig. 6 in comparison to the motor B/BB scenarios. This can be theoretically explained by the fact that motors A and C are low-inertia motors, unlike motors of type B [31]. More inertia is known to be related to less severe oscillations and instabilities (e.g. see [46]), even when provided from the consumption side [49,50]. Furthermore, the deceleration of induction motors causes them to draw higher current, which leads to further voltage depression. This affects the STVS negatively [46]. Hence, all else equal, lower inertia enhances oscillatory peaks after faults, which reflects on system voltage deviations and ultimately short-term voltage stability of the system.

Regarding motor type D, after 25% of the dynamic load share, they start to increasingly trigger instabilities. This occurs due to the initiation of the FIDVR event, leading to a depressed voltage profile with a duration of several seconds, followed by an overvoltage spike. This overvoltage spike is categorised as instability by the presented methodology. However, by carefully examining the graphs it can be seen that some of these scenarios could as well be called stable. This depends largely on the used threshold and the protection operation of the system in question since voltage tends to stabilize shortly. An example of such a graph is shown in Fig. 7.

As seen from Fig. 7, the scenario could be called inherently stable for some systems since the voltage does eventually stabilize, but it also surpasses the 1.2 per unit threshold used in the study (see section 3). We argue that this high overvoltage would likely lead the grid into a dangerous operating state, possibly causing further protection operations and cascading faults. Therefore, these results are also categorised as (potentially) unstable. However, to elaborate more on this, section 4.3 conducts a further investigation.

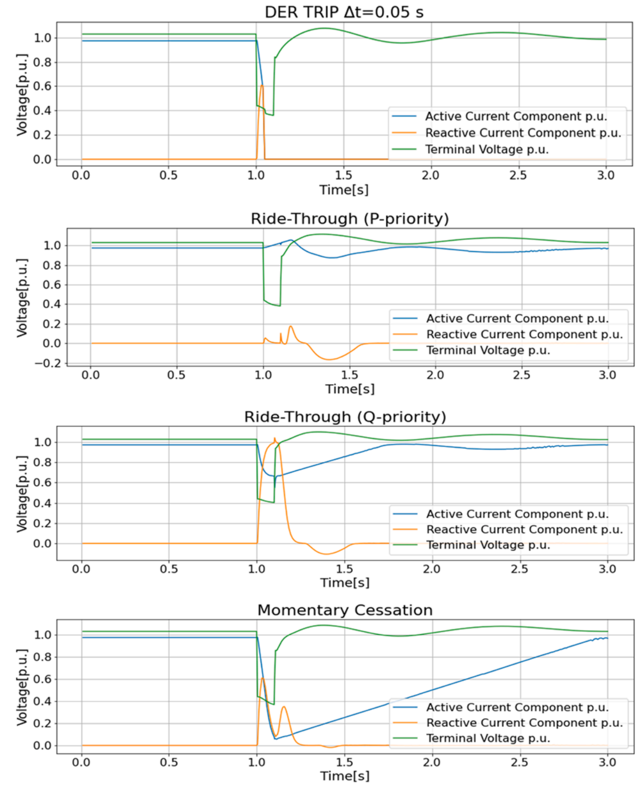

Fig. 8. Four fault control strategies of the DER_A model used in the analysis and their active/reactive current components after being subjected to a terminal bus voltage drop.

Overall, it can be concluded from this section that dynamic loads play a significant role in STVS, as theoretically expected. The novel contribution is the insight into what percentages of dynamic load are expected to lead to STVS, as well as which types of induction motors are more strongly correlated with the inception of STVS.

4.2. Influence of dynamic loads and advanced DER modelling on STVS

For the second part of the analysis, the system from section 4.1 is taken as a basis. Hence, all 11 WECC Composite Loads are kept in the grid, with a fixed share of 50% in comparison to the static load. This corresponds to the central part of the last column of the heatmap in Fig. 6.

Research questions addressed in this section are as follows:

3. *How do DERs interact with dynamic load and the grid itself in terms of STVS?*
4. *Are DERs beneficial or detrimental to STVS? If so, what penetration amounts make a difference?*
5. *How do different DER control strategies affect these results?*

All three research questions are vastly unexplored in the existing literature, even though the latest definitions of STVS specifically

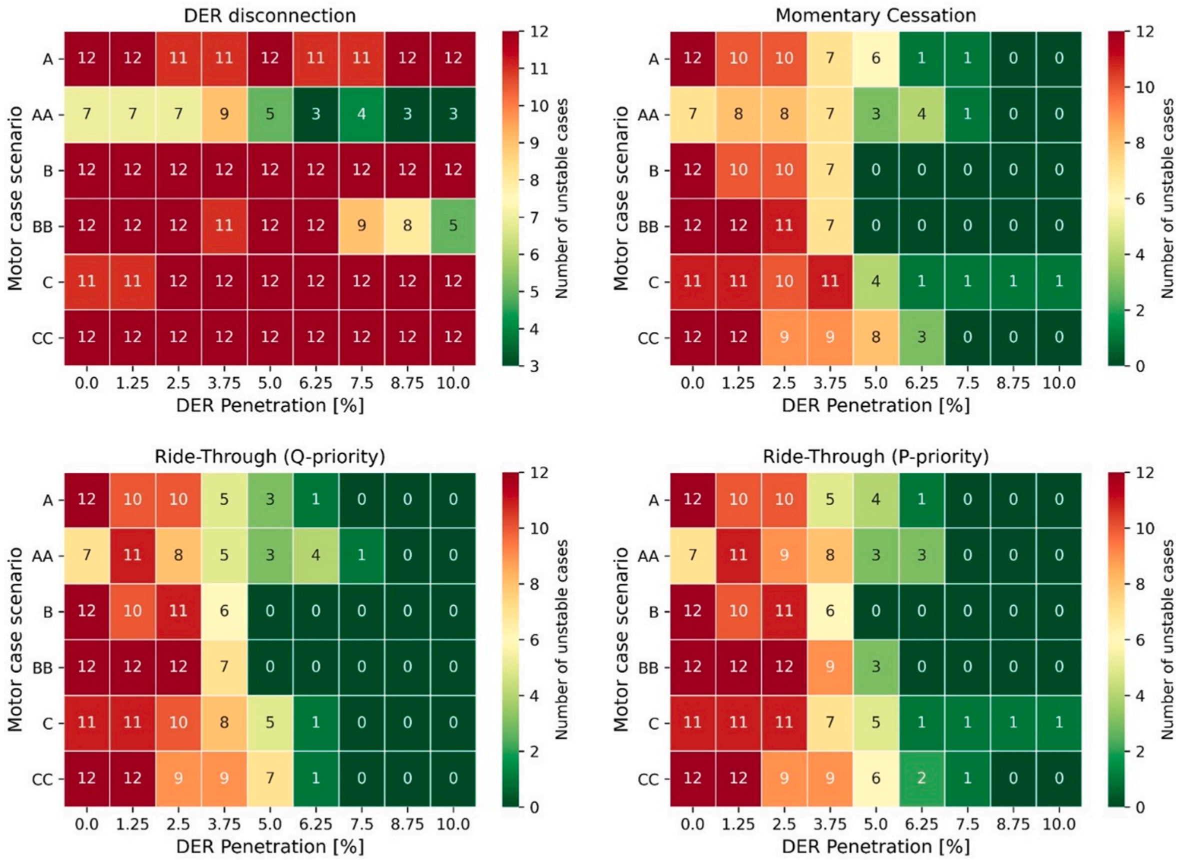

Fig. 9. Correlation heatmaps of various DER control strateges' influence on short-term voltage stability a) DER disconnection; b) Momentary Cessation; c) Ride-Through (Q-priority); d) Ride-Through (P-priority).

mention inverter-based generation and its potential influence on the phenomenon [46].

Six out of ten scenarios are analysed, i.e. cases A, AA, B, BB, C, and CC from table 2. Cases D and DD are separately addressed in section 4.3, while cases 0 and N would not help with demonstrating different dynamic load type influence on STVS in the presence of DER units, and are therefore omitted. DERs have been added in the same 11 busbars where dynamic loads are located (see table 1 and Fig. 2). The amount of DER is varied in the range of 0 to 10 percentage of the total generation of the system, with 1.25% incremental steps. This allows evaluating how different penetration scenarios in the grids affect STVS.

It should be noted that the DER generation is effectively replacing synchronous generation, not complementing it, making it more realistic and more voltage stability constrained. Hence, for instance, the maximum of 10% penetration results in 936 MW of DER infeed spread out in the central region, considering the total sum of synchronous generation in operating point A [41].

Furthermore, to address the third research question of this section, four different fault control strategies are analysed. The strategies are selected as the most common ones seen in the DER operation [7], as well as in grid studies that utilize the DER_A model [51].

- DER disconnection shortly after a fault ($\Delta t = 0.05$ s)
- Ride-through with Q-priority
- Ride-through with P-priority
- Momentary Cessation

The example fault responses of a single DER unit with each of the fault control strategies are shown in Fig. 8.

Fig. 8a shows the DER disconnection strategy. The majority of DER units (especially smaller ones) in grids still exhibit this kind of behaviour for a severe voltage drop, although more recent regulations, like the new IEEE standard [52], introduce more strict regulations for the DER ride-through.

However, the problem remains since a vast majority of DER were installed and are still operated based on the older standards that do not have such requirements.

In the analysed setup, the DER unit is set to trip 50 ms after the fault inception. In Fig. 8b and 8c, P-priority and Q-priority fault ride-through control strategies are shown, respectively. After the fault inception, the DER provides voltage support to the grid either by prioritizing active (8b) or reactive (8c) current, with differences seen in the graphs. In Fig. 8b, due to the P-priority setting, the active current component is kept near the maximum converter current (1.2 per unit), hence almost no reactive current can be provided. In Fig. 8c, the reactive current component is prioritized, which results in its sharp increase following the disturbance.

After the fault is cleared, the operation is continued with pre-fault settings. As distribution systems generally contain cables rather than overhead lines, it is theoretically expected that purely reactive power support would be suboptimal in terms of voltage improvements, due to the higher R/X ratio of the grid. However, some studies show that this is not always the case [22,49], hence both strategies are analysed in this study independently to shed more light on this phenomenon.

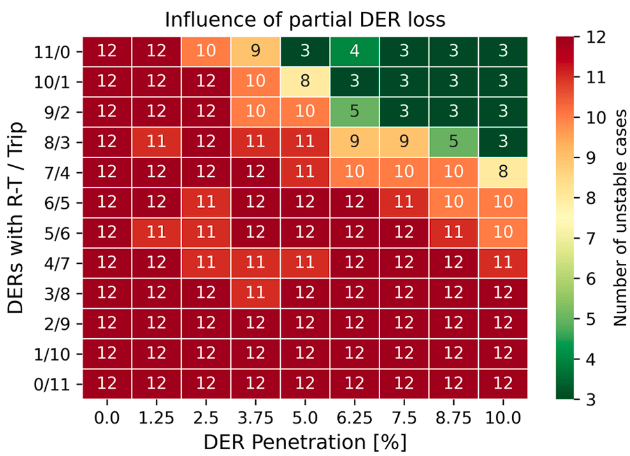

Fig. 10. Correlation heatmap of combined DER disconnection (Trip) and DER Ride-Through (R-T) influence on STVS.

Finally, Fig. 8d shows another fault control strategy used in modern DER units, momentary cessation. As soon as the voltage drop is detected, the unit drops its active power output to zero in a steep ramp decline. After the fault is cleared and voltage recovers, the unit ramps up the power output to its pre-fault value.

The same 12 fault scenarios from table 1 are used, with heatmaps for result visualization. The results are shown in Fig. 9, containing over 2500 dynamic RMS simulations created through the presented Python-PowerFactory framework. Detailed DER parameters are shown in the appendix.

The first column of all four heatmaps is effectively the same as the (middle part of the) last column of Fig. 6. For Fig. 9a, units are set to trip 50 ms after the fault inception. By introducing more penetration of renewable energy, overall, it can be seen that the system's STVS does not improve. Furthermore, since this amount of lost generation would cause other issues (i.e. power imbalance, frequency deviations, see section 4.3), the effect can be described as detrimental to STVS and the overall grid resilience.

If a ride-through fault control strategy is used, different correlations are seen, shown in Fig. 9c and 9d. Firstly, differences in P-priority and Q-priority heatmaps are very subtle, hence the same conclusions can be derived for each. For penetrations of 0 to 2.5% of the total system generation, slight improvements in STVS are spotted. However, from 3.75% penetration, the effects are more clearly visible, with most of the scenarios being stable for 6.25% or more of DER penetration.

For Fig. 9b and the momentary cessation control strategy, results are slightly worse than with the ride-through, however still similarly beneficial.

The beneficial effects of these three strategies can be theoretically understood by considering that DER will provide local voltage support in the grid, effectively reducing voltage excursions of busbars where the dynamic load is connected, indirectly preserving STVS. The more such voltage support exists in the grid, the more resilient the system is to short-term voltage instability. In terms of obtained values, it can be concluded that roughly about 5% of local DER generation (in terms of total system generation) is already enough to mitigate most of the possible STVS issues *if* ride-through or momentary cessation is used. Furthermore, scenarios with more A and/or C type of motor are once again shown to be more correlated with short-term voltage instability, i.e. being harder for DERs' voltage support to mitigate. This aligns with the results obtained in section 4.1, which can be physically understood

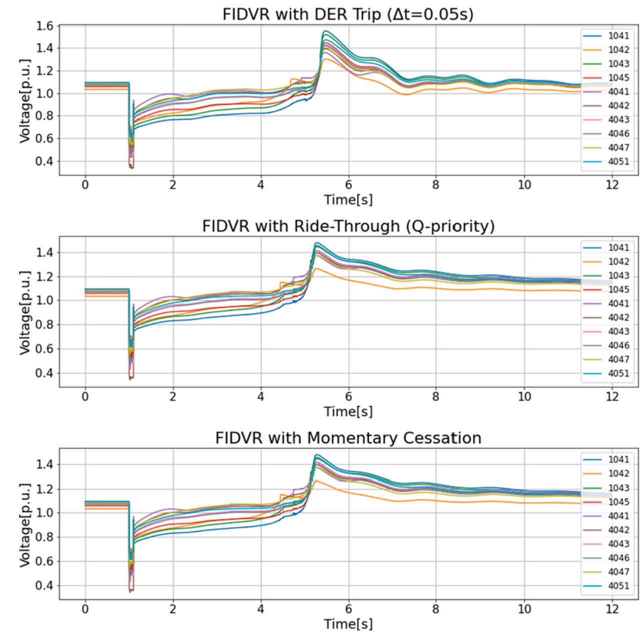

Fig. 11. Transmission system voltages during a FIDVR event with different DER control strategies.

due to the lower inertia of such induction motors (e.g. compressor motors, centrifugal pumps, etc.). This leads to higher voltage oscillatory peaks, and consequently, more severe voltage excursions and higher susceptibility to short-term instabilities that are harder for DERs' voltage support to mitigate.

Nevertheless, one should note that many older (or smaller) DERs in the grid do not have ride-through or momentary cessation control strategies (or fail to perform them), hence this percentage effectively increases in practical scenarios. To evaluate to what extent does DER disconnection correlate with the short-term voltage instability, in comparison to the units that ride-through, another analysis is conducted. Fig. 10 shows a heatmap with an increasing (decreasing) number of the trip (ride-through, Q-priority) DER units on the Y-axis, while X-axis varies the total penetration of DERs in the system. The effects are evaluated for the 12 mentioned fault scenarios once again, as well as a 50% share of WECC Composite Load compared to the static load. This time, equal-share load composition scenario N (see table 2) is chosen for all the simulations, since individual motor-type effects have already been evaluated. The simulated scenario is conducted using the same software setup as previously described.

As previously shown, these results confirm that a high amount of dynamic load causes instability in the large majority of cases, and low amounts of DER penetration are unable to mitigate this. Furthermore, with higher DER penetration, less instability is seen across the two analysed scenarios. However, there is a clear difference between a trip and a ride-through correlation with STVS. If the majority of DER units disconnect (bottom part of the heatmap), even high amounts of penetration are not providing any benefits to STVS. On the other hand, a high number of Ride-Through (R-T) DER units (top part of the heatmap) shows clear improvements. The most impactful finding of this analysis is actually how overwhelming is the influence of disconnecting DERs in comparison to the R-T units. By observing cases with a similar number of trip and R-T units (middle rows), the system remains unstable in the majority of cases. Only when the number of R-T units is roughly double in comparison to the number of trip units, we start to see stability improvements. This provides a clear insight into how strongly DER disconnection is correlated to short-term voltage instability, being about twice as detrimental to the STVS in comparison to the benefits of R-T units' voltage support in this analysis. Practically, this implies that in a voltage stability stressed system, for each megawatt of DER lost, the studied system needs roughly two megawatts of voltage-supporting DER which rides through the fault so that the overall effect of distributed generation on bulk power system STVS is neutral. While this ratio is not a precise rule, as it depends on the specific system, it is still likely that the general takeaway holds for most of the systems. On a positive note, the overpowering of DER disconnection's detrimental effect over DER R-T beneficial effect diminishes for higher DER penetration (top-right part of the heatmap), suggesting that in very high DER penetration scenarios the situation becomes less severe.

It should be noted that the entire analysis is established on the IEEE system from Fig. 2, which is dominantly based on synchronous generation. While a decrease (increase) of synchronous generation (renewable generation) in terms of large units is not addressed in the study, it can be expected that most of the obtained results would be further emphasized in a modern grid with overall less inertia and less voltage (reactive power) support. Therefore, the results are rather conservative in such a perspective.

4.3. Fault-Induced delayed voltage recovery

Fault-Induced Delayed Voltage Recovery is a phenomenon in which system voltages remains at excessively low levels for several seconds, even after the fault has been cleared successfully [53]. The root cause of these events is mainly attributed to the stalling of single-phase induction motors, e.g. A/C units, which causes excessive reactive power demand in the post-fault phase. These units are represented by a type-D motor in the WECC Composite Load model. More detailed information about the phenomenon, its causes, and implications can be found in [53–56].

This section is dedicated to explaining cases of high type-D motor presence in the grid and their interactions with DERs and STVS further. Using the WECC Composite Load Model, FIDVR can be simulated by incorporating a larger amount of Motor type D in the model.

Fig. 11 shows an example of a voltage response of the transmission grid for three DER fault control strategies, i.e. disconnection, Ride-Through with Q priority, and Momentary Cessation (see section 4.2). For all three cases, penetration of DER is set to a maximum analysed penetration case of 10% of total system generation, while the share of motors is set to case DD (see table 2).

By observing the graphs, it can be seen that a similar FIDVR phenomenon occurs in each case, without significant differences in terms of voltage trajectory. This is in line with the theoretical expectations, as FIDVR is an extensively explored phenomenon largely attributed to the single-phase A/C units [54]. Hence, even in such significantly different DER scenarios that showed strongly beneficial or detrimental effects on STVS in previous sections (depending on the type and penetration specifics), the resulting influence on voltage profile during the FIDVR phenomenon is negligible.

Nonetheless, the spike in the voltages after all the D-type motors have disconnected may cause further disconnections depending on the overvoltage protection settings of the specific system's equipment in question. Furthermore, a long-lasting low voltage profile in the seconds following the fault is expected to cause many DER units to disconnect since such a voltage profile would likely be below the low voltage ride-through (LVRT) voltage–time curve. To demonstrate this effect, let us have a look at Fig. 12, which shows the frequency of the synchronous generators in the grid for the case studied in Fig. 11a, in which DER units disconnected.

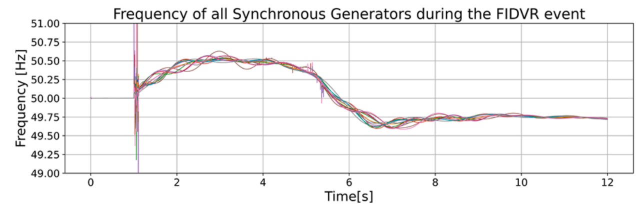

Fig. 12. System frequency measured on all synchronous generators in the system (see Fig. 2) throughout the FIDVR event.

As a result of a 3-phase short-circuit, the frequency deviation begins. Several seconds after the fault clearing, frequency settles on a stable value. However, this value is 49.75 Hz in comparison to the pre-fault value of 50 Hz. This difference can be explained by taking into account two factors. Firstly, a large amount of D-type motors in the grid has stalled, resulting in thermal protection trips just around t = 5 s. Naturally, this value depends on the D-motor thermal protection settings, but the same results (just time-shifted) hold for any practical settings. More information about this can be found in [54]. The result of the FIDVR event is a loss of a significant part of the load. We would expect the grid frequency to be higher than 50 Hz in such a case, but there is another effect to consider here. All the DER units that disconnected due to the low-voltage profile and overvoltage spike also cause power imbalance. These two factors drive the frequency in opposing directions. In some cases, they can effectively cancel each other out, as shown in [57], but in a case where a large DER penetration is present, it is more likely that a low-frequency situation occurs in the post-fault phase, as seen in this scenario, where DER disconnections dictate frequency excursions. More future research in this direction would be beneficial. For more information about this topic, [7,57] present some insights.

Additionally, certain DER control parameters might affect these results. For instance, the ramp-up speed of the momentary cessation control strategy may delay the recovery of DER units. The utilized values of LVRT disconnection, both in terms of undervoltage and overvoltage settings, may also result in more or less DER disconnection throughout the FIDVR, in comparison to the demonstrated cases. These parameters are also strongly connected to the country-specific grid codes. Therefore, the parameters should be treated with consideration of the regulations. Nevertheless, a follow-up study related to the parameter sensitivity would be beneficial.

Regarding STVS, we conclude that overall, there is a very low relation between different DER control strategies and FIDVR, as theoretically expected. The main drivers of the event are D-type motors such as A/C units. Therefore, their accurate modelling, unlike DER modelling, is crucial for FIDVR studies. However, if the overall system impact is analysed, including advanced DER models may provide better insight into frequency deviations and power imbalances, as a consequence of DER disconnections due to the FIDVR event.

5. Conclusion

The impact of the dynamic load and DER presence on the short-term voltage stability of a power system is investigated in terms of different penetrations, types and control strategies. The extensive simulation results suggest which load and generation specifications mostly contribute to the short-term voltage instability.

In terms of dynamic load, it has been shown that by increasing the share of induction motors in the grid, voltage oscillations and excursions become more pronounced. With the amounts starting from 30% dynamic load in the framework of this study, the bulk power system starts experiencing potential short-term voltage instabilities. With the dynamic load share approaching 50%, most of the simulated cases become unstable after a fault. Furthermore, it has been shown that low-inertia types of motors are the most detrimental to the STVS, as they tend to enhance voltage oscillations further.

When a system contains a significant infeed of DER units, this can be either detrimental or beneficial for the STVS, as shown in the study. The key factors here are the penetration amount of DER and their respective control strategy. It has been shown that DER disconnection shortly after the fault is detrimental to STVS in almost all scenarios, while on the contrary, ride-through and momentary cessation strategies can suppress voltage oscillations and excursions initiated by the fault response of the dynamic load. In terms of the penetration amounts, it has been shown that roughly, 3–5% of DER penetration in comparison to the total system generation is already providing visible benefits to STVS. More than 5% exhibits strong correlations with the preservation of STVS. Moreover, the negative impact of DER disconnection is demonstrated to be only partly offset by an equally positive impact of the ride-through share of DER. Finally, FIDVR is briefly analysed where it is shown that it exhibits low correlations with DERs' penetration and their operation and that it is mainly driven by single-phase A/C units, i.e. motor type D, as theoretically expected. However, it should be noted that FIDVR effects on frequency deviation and power imbalance are strongly correlated with the DER infeed and post-fault response.

We conclude this study with a clear verdict that dynamic load and DER units play an important role in distribution-transmission interactions. It has been shown in what amounts and in what compositions are dynamic loads the most detrimental to the STVS, while DER units are shown to be either beneficial or detrimental, depending on various specifications studied in the paper. Consequently, the paper provides an enhanced understanding of the STVS phenomena and its driving forces in modern power grids.

With the current strategic direction of the power systems towards low-emission of greenhouse gases, it is expected that dynamic load presence and DER penetration will increase rapidly, leading to a potentially compromised short-term voltage stability. Furthermore, with the overall system generation shift towards low-inertia and limited voltage support renewable resources, these effects will be further emphasized in the future.

Finally, a detailed analysis of DER and dynamic load influence on a particular system's dynamics is shown to be necessary for assessing the voltage stability accurately. Hence, the research should continue toward advanced monitoring and control strategies where distribution system dynamics are also considered. This kind of analysis would allow predictions of disturbances and their consequences in real-time, as well as open possibilities for mitigation solutions. In terms of STVS, it is also advisable to apply stricter DER grid codes in the future, to maximize the number of voltage-supporting units and consequently minimize the number of DERs that disconnect during and after a disturbance.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

The parameters that are not mentioned in these tables nor the paper are kept at their default PowerFactory 2020 SP2A values, which can be found in the PowerFactory templates of the WECC Composite Load model and DER_A model.

The IEEE Test System for Voltage Stability Analysis and Security Assessment can be downloaded from the following link: https://cmte.ieee.org/pes-psdp/489–2/.

The methodology based on Python-PowerFactory scripting and the utilized PowerFactory model will be further elaborated in another publication, as a useful method to overcome the complexity of big data and a large number of variables in modern power system analyses. For any further questions, the reader is advised to contact the corresponding author.

Values in Table A1 are based on the PowerFactory default settings. The disconnection time of 0.05 s is added to DER Disconnection scenarios, based on [7]. Furthermore, parameters edited in the Momentary Cessation cases are selected to allow DER units to enter Momentary Cessation control mode during the selected fault scenarios. All the other parameters are listed in Table A2.

Table A1
DER_A relevant parameters used for simulations in Fig. 8, Fig. 9 and Fig. 10.[1]

Parameter	Description	DER Disconnection	DER Ride-Through (P-priority)	DER Ride-Through (Q-priority)	Momentary Cessation
Δt	Disconnection time after the fault	0.05 s	N/A	N/A	N/A
vl0	Voltage break-point	0.15 pu[2]	0.15 pu	0.15 pu	0.5 pu
vl1	Voltage break-point	0.9 pu	0.9 pu	0.9 pu	0.8 pu
tvl0	Timer for vl0	0.1 s	0.1 s	0.1 s	1.5 s
tvl1	Timer for vl1[3]	1.5 s	1.5 s	1.5 s	0.5 s
Vtripflag	Enable voltage trip	0	0	0	1
Pqflag	P/Q Current priority	1	1	0	0

[1] Fig. 10 uses only DER Disconnection and DER Ride-Through (Q-priority)
[2] For DER disconnection control strategy, parameters other than Δt do not play any role in post-fault DER response
[3] For more information about the parameters, see[40]

Table A2
DER_A parameters held constant in the analysis.

Parameter	Description	Value
Trv	Transducer time constant (volt.) [s]	0.02
Vref0	Voltage ref. set point [pu]	−1
dbd1	Lower voltage deadband [pu]	−0.05
dbd2	Upper voltage deadband [pu]	0.05
Kqv	Prop. Volt. Control gain [pu/pu]	5
Tp	Transducer time constant (power) [s]	0.02
PfFlag	Freq. control flag	1
Tiq	Q control time constant [s]	0.02
Trf	Transducer time constant (freq.) [s]	0.1
Freq_flag	Freq. control flag	1
Ddn	Freq. droop gain (down-side) [pu/pu]	20
Dup	Freq. droop gain (up-side [pu/pu]	0
fdbd1	Lower freq. control deadband [pu	−0.004
fdbd2	Upper freq. control deadband [pu]	0.004
Kpg	Active power control prop. gain [pu]	0.1
Kiq	Active power control integral gain [pu]	10
Tpord	Power order time constant [s]	0.02
Imax	Max. converter current [pu]	1.2
Tg	Current control time constant [s]	0.02
vh0	Voltage break-point for HV cut-out [pu]	2
vh1	Voltage break-point for HV cut-out [pu]	1.1
tvh0	Timer for HV break-point (vh0) [s]	0.1
tvh1	Timer for HV break-point (vh1) [s]	1.5
Vfrac	Fraction of units that recovers (0…1)	0.7
Tv	Time constant-output volt. cut-out [s]	0.02
Ftripflag	Frequency tripping	1
fl	Freq. break-point for low freq. cut-out [Hz]	47.5
fh	Freq. break-point for high freq. cut out[Hz]	51.5
tfl	Timer for low freq. break-point (fl) [s]	0.3
tfh	Timer for high freq. break-point (fh) [s]	0.3
Vpr	Min. volt. To disable freq. tripping [pu]	0.8
Iql1	Min. limit of reactive current injection [pu]	−1
femin	Frequency control min. error [pu]	−99
Pmin	Minimum power [pu]	0
dPmin	Min. power ramp rate (down) [pu/s]	−0.5
Iqh1	Max. limit of reactive current injection [pu]	1
femax	Frequency control max. error [pu]	99
Pmax	Max. power [pu]	1.1
dPmax	Max. power ramp rate (up) [pu/s]	0.5
rrpwr	Max. power rise ramp post fault [pu/s]	0.5

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