Impact of Active Distribution Networks on Transient Stability

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***Abstract*— The increasing penetration of distributed energy resources (DERs) has turned passive distribution networks into active, in turn affecting the dynamic behavior of the system. It is essential to investigate to what extent transmission system dynamics are affected by these changes. This paper aims at identifying the impact of active distribution networks (ADNs) on transient stability. The studies consider two main scenarios. In the first, same initial conditions are considered in an attempt to investigate the effect of ADN dynamics alone. In the second, pre-fault operating conditions are also varied in a realistic manner through generation of representative daily profiles for load and renewable generation. The impact of fault, ADN, and critical SG location is investigated. In addition, the response of DER control and protection to short and longer faults highlights how different aspects of transient stability are affected.**

***Index Terms*-- active distribution networks, distributed energy resources, representative profiles, transient stability.**

I. Introduction

Traditionally, dynamic simulations are performed by transmission system operators for transient stability assessment. A common approach for the representation of distribution networks in transmission level studies is to use a single lumped load behind an equivalent feeder to represent the load under the distribution substation [1]. However, recent changes in distribution systems with the introduction of distributed energy resources (DERs) has made conventional systems operate as active components. Furthermore, these new technologies, are mostly converter interfaced generators that support new grid code requirements and functionalities that are affecting system dynamic behavior, which was until recently dominated by synchronous generators (SGs). It's worth noting that DER installations are expected to increase in the following years. In United Kingdom, DER penetration is forecasted to reach up to 100.5 GW by the end of 2050 as reported in the Future Energy Scenarios (FES), by National Grid Electricity System Operator [2]. These challenges necessitate the consideration of DER dynamic behavior when assessing transient stability. It is also important to account for different operating conditions, various DER penetration levels (PLs), and generally the spatio-temporal variability that is associated with active distribution networks (ADNs). Driven by the need of considering DERs in an aggregate manner for system stability studies, a state-of-the-art dynamic model has been introduced by Western Electricity Coordinating Council, known as der_a [3]. Studies [1] and [4] utilize the aforementioned model to look into the impact of DERs on the bulk power system (BPS), but focusing on the parameterization of the model and the extensions on voltage and frequency stability and reliability studies.

The contribution of DERs to BPS control and stability is investigated in [5], though only some indications regarding angular stability are given and the authors highlight the need for respective studies. In [6] the allowable level of DER penetration is assessed considering scenarios with different modelling approaches of loads and DERs (using der_a model for the dynamic representation), taking into account transient and steady state contingencies, and the impact of load variations. However, rotor angle stability is not investigated. In [7] some basic features of the interaction of transmission – distribution system on voltage, frequency, and transient stability are highlighted. The transient stability assessment is based on two scenarios that consider voltage control and reactive power regulation, while the rest of the factors associated with DERs operation are not investigated. A case study of Namibia investigates the impacts of DERs on transient stability, with the studies being restricted to a single fault location considering two extreme PLs [8].

The main objective of this paper is to investigate the impact of ADNs on power system transient stability by utilizing the der_a model for representing the respective dynamics. The focus is on highlighting aspects related to the dynamic behavior of ADNs including locational aspects as well as the impact of different operating conditions introduced by different PL of DERs and the variability of load and renewable generation. The quantification of this impact is

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All results can be fully reproduced using the methods and data described in this paper and references provided

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implemented by means of two indices that reveal different aspects of how transient stability is affected. Two main categories of case studies are included. In the first one, the initial conditions are kept constant in an attempt to capture the impact related to DER dynamic behavior alone. In the second, the overall impact, coming from: 1) variations in pre-fault conditions and 2) the dynamic behavior, is studied. To account for different operating conditions, representative daily curves are extracted from historic data for load and DERs (photovoltaics -PV and wind). In addition, both short- and long-term faults are examined to investigate the respective behavior of DER units which can be affected from their disconnection following longer duration faults.

II. Methodology

A significant mechanism that influences transient stability is the variation of pre-fault conditions. In this regard, the first set of case studies consider the same initial conditions to capture the effect of the dynamic behavior of ADNs exclusively. However, in reality, the initial conditions are constantly changing due to load, wind, and PV variations, leading to different mix of load/generation patterns. This aspect is investigated using representative daily curves. This approach, combined with the ability of the der_a model to represent the detailed response of ADNs to voltage and frequency excursions, can quantify the overall impact of ADNs on transient stability over a wide range of realistically derived operating conditions. Transient stability assessment is carried out through a large number of RMS simulations. A three phase, self-clearing fault is applied sequentially on each of the lines while the location of the der_a models also changes to identify the respective locational aspects. Another important variable affecting the dynamic response of the system is fault duration. On top of well-studied effects of fault duration on transient stability, a particular aspect related to DER response is the tripping of several or all DER units. In order to identify the effect of this implication, the first category of case studies includes long duration faults (the maximum time that the system can endure the fault without losing synchronism) while the second involves shorter duration faults (100ms duration).

A. Transient stability indices for the evaluation of DER impact on system stability

The simulation results are analyzed with the help of two transient stability indices which are briefly described below. Longer faults are examined through CCT, while short-term faults are investigated by means of transient kinetic energy (TKE). CCT is defined as the maximum time that is allowed to remove the disturbance before the system loses synchronism. CCT is generally a very informative index as it provides an indication of the stability boundary and in this context, it can also reveal aspects associated with dynamics during longer faults. In this paper, the CCT is calculated by iteratively increasing the fault duration and performing time domain simulations in order to capture in detail dynamics related to ADNs. The maximum fault duration considered in this paper is 0.7 sec, after which the system is considered to be very stable. The generators' TKE, which is the extra energy gained by rotors during a contingency, is given by (1),

$$TKE = \sum_{i=1} \frac{1}{2} J_i \cdot \Delta\omega_i^2, \tag{1}$$

where, J_i and $\Delta\omega_i$ are the angular momentum of the rotor at synchronous speed and the speed deviation of the i-th generator immediately after the fault clearance. TKE has been observed to have good sensitivity when multiple conditions are studied [9]. In addition, it can reveal particular aspects related to the acceleration during the fault.

B. Representative profiles

In order to capture a variety of operational conditions, historic datasets that reflect the variations within a year can be used. Due to computational restrictions though, it would not be feasible to utilize the entire annual timeseries. Considering, however, that such decisions are, for the most part, driven by a small number of operating points (e.g. peak electrical demand), it is proposed to use nine representative daily profiles which are created based on feature selection, i.e., 1 average weekday per season, 1 Saturday average profile, 1 Sunday average profile, the hottest and coldest day of the year, and finally the day with the highest load indication [10]. In this paper real data from UK National Grid (demand and distributed generation (DG) with sampling time of 30min, i.e., 48 values for each daily profile) available for 2020 are used [11]. Specifically, all days of the year are classified to the above 9 categories. Apart from the three last classes, which are distinct daily profiles, the rest average profiles are calculated by averaging the data that belong to their own category per half-hour interval· this way taking into account both the magnitude and the shape of the daily curves. This way, the successive snapshots provide realistic combinations of load and DG levels throughout a day and can consequently highlight the impact of ADNs on transient stability for representative days throughout the whole year. Fig. 1 demonstrates the derived profiles of all representative days, depicting gross load (i.e., net load plus DG) along with the corresponding PV and wind DG. The values are normalized with the maximum gross load indication of the year. The resulting profiles cover a range of representative cases for different levels of load, wind, and PV generation as well as load/generation mix.

C. Der_a model

The der_a model is a positive-sequence model able to represent the aggregated behavior of DERs (both legacy and new technology) in distribution systems. The model accommodates 48 parameters and 10 states and many functionalities like: active power-frequency control, frequency tripping, reactive power control based on power factor, proportional voltage control, post fault active power recovery, voltage partial tripping, and reconnection with corresponding time delays and a voltage source network interface [1], [3]. Different sets of parameter values can be used to represent variations of different standards such as the different IEEE Std. 1547 vintages. In this study, the specific parameter values used correspond to a mix of 30% for the 2003 vintage and 70% for the 2018 vintage which are fully described in [3] (see Table 3.1 from reference [3]). This implementation can also reveal the effects of momentary cessation and tripping of DER units on dynamic system behavior.

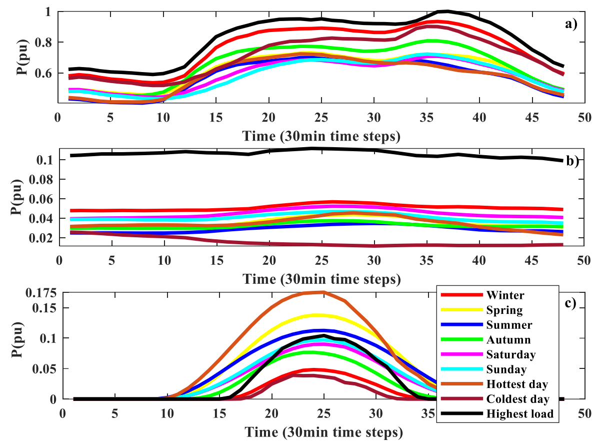

Figure 1. Active power of representative profiles for a) load, b) wind and c) PV generation.

III. TEST SYSTEM AND DESIGN OF CASE STUDIES

In this paper, a modified version of the 9 Bus System, shown in Fig. 2, is used and implemented in PowerFactory/DigSilent [12]. SGs and nominal load data are specified in Fig. 2. SG2 is equipped with an IEEE type 1 automatic voltage regulator and a power system stabilizer. The operating region of SGs for active power is assumed to be ranging from 0.3 pu to 0.85 pu of S_{rated} while reactive power limits are from -0.25 pu to 0.5 pu of S_{rated}. The demand is modelled as balanced three-phase constant impedance loads. Extra transformers are added to the original version of the system to attach the der_a models and the loads to the transmission system.

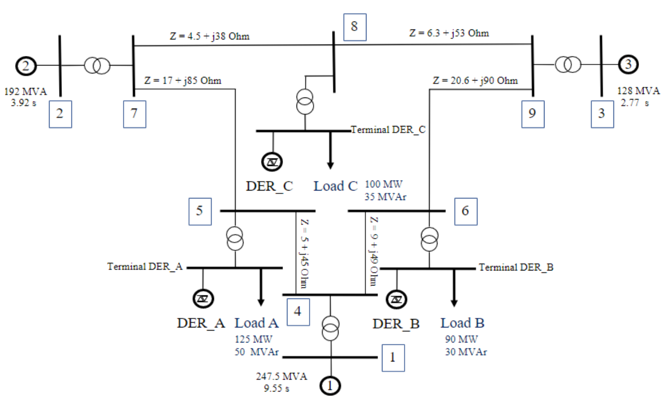

Figure 2. Modified version of 9 Bus System.

A. *Case studies*

The test cases considered are separated into two main scenarios. In scenario 1, same initial conditions are preserved in a pursuit to focus on the dynamic behavior of the der_a model itself and not the effect different operating conditions might have. In the second scenario variable initial conditions are used to account for a more realistic approach. The SG dispatch is determined by an AC optimal power flow (OPF) assuming that SG1 has the highest incremental cost, leading to higher loading of the other two SGs.

1) *Scenario 1: Same initial conditions*

In the first scenario, 64 distinct case studies are formulated to investigate the impact of the dynamic behavior of DERs, for different amount and location of DER units connected. More specifically, the cases are developed to preserve the power flow constant between the transmission and distribution network. In this regard, for every increase in the generation of der_a models, the active power of the corresponding loads increases proportionally so that the net load seen at the transmission network boundary remains the same, while the reactive power remains constant. A description of the cases is given in Table I. Case 1 is the base case with no DERs and is considered the reference point; the respective load values are shown in Fig. 2. In Cases 2-10 only DER-A is in service, and its generation is increasing in ascending order alongside Load A as the case number increases, by the same amount, i.e., 13.5 MW. Similarly, the process is repeated for other locations as well as for cases where multiple der_a models are in operation in combinations of locations. For example, in case 37 all der_a models are in service and each one of them generates 121.5 MW. Additionally, Loads A, B and C increase by 121.5 MW from the base case (Case 1) each, to 246.5 MW, 211.5 MW and 221.5 MW, respectively.

TABLE I. CASES WITH SAME INITIAL CONDITIONS

Der_a models in service	Cases	Der_a models in service	Cases
No der_a model	1	DER-A, B, C	29-37
DER-A	2-10	DER-A, B	38-46
DER-B	11-19	DER-A, C	47-55
DER-C	20-28	DER-B, C	56-64

2) *Scenario 2: Variable initial conditions*

In this scenario, the representative profiles are incorporated into the 9 Bus System. For every daily profile the following procedure is followed: for each 30-min interval the total DG power is used as the reference input active power (parameter Pref) for the der_a models and respectively the load power for the load models of the system, thus forming the initial operating point. Subsequently, an AC OPF is solved to define the SG dispatch and afterwards the RMS simulation is executed both for short- and long-term faults to calculate the transient stability indices. All three der_a models are in service. In order to investigate aspects related to the dynamic behavior of DERs and compare among cases, a different approach is followed in this scenario by considering the gross and net load as necessary. Net load is the load seen at the transmission network interface, while gross load is the net load plus the distributed wind and PV generation. In the first instance, only the net load is considered which means that DERs are only considered as a reduction of the total load and their dynamic behavior is not modelled. In the second instance, simulations are executed considering gross load and the corresponding der_a models are also connected. Consequently, this approach considers the DER dynamics, including the tripping settings. Comparing these two approaches highlights the extent of deviation transient stability indices can have for various operating conditions, when DER dynamic behavior is neglected in such studies. It is worth noting that for the studies in this paper, the average PL of DERs for 2020 from UK National Grid data is used, which is about 10% of gross load. Hence, the effect of ADNs is expected to be relatively small, yet the derived patterns from the systematic evaluation of all representative profiles generate useful information and identify resulting trends. Furthermore, to ascertain the derived results the simulations are repeated for average PL of 20% utilizing the 2025 PV, wind and load variations based on UK National Grid FES [2].

IV. Results

A. Impact of same initial conditions investigating locational aspects and fault duration

Regarding study cases with the same initial conditions, results are analyzed with the help of figures showing the % deviation of each index for every single case compared to Case 1. In particular, Fig. 3 presents the CCT, and Fig. 4 the TKE. One of the main attributes arising is that locational aspects have a significant impact on transient stability, leading to either improvement or deterioration. For this specific network and case studies, the main trend reveals deterioration of transient stability. It is observed that when the fault occurs far from (in terms of total impedance) the critical SG (CSG), i.e., SG3, the corresponding der_a which is closer to the CSG, causes the highest variations in the two indices. In fact, the bigger the distance of the der_a model with respect to the fault location the bigger the deviation is. Especially when the fault is located on lines 4-5, 4-6, 6-9, and 5-7 the increase of DER-C size appears to cause an almost linear decrease on the CCT (up to 30%) and an increase on TKE (up to 150%), which both indicate deterioration with respect to transient stability. Specifically for the shorter faults, only deterioration is observed, i.e., TKE always increases as DER size increases for all DER and fault locations. This indicates that the kinetic energy obtained particularly during the acceleration phase of SGs is increasing. In addition, the largest increase is observed when all der_a models are in service.

For fault locations near the SGs (3&2) which are more prone to lose stability (i.e., lines 8-9, 7-8), the DER unit closest to them, i.e., DER-C, has no practical impact for longer faults. On the contrary, there is a slight increase of CCTs (up to 7%) when distant DERs size increases for these fault locations.

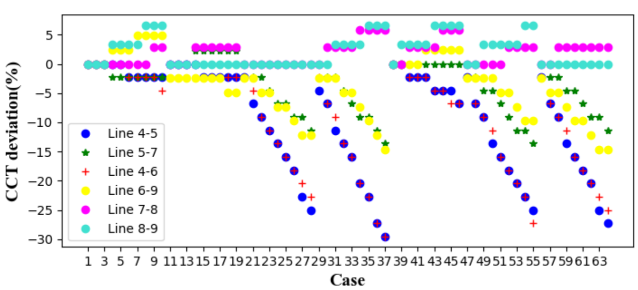

Figure 3. CCT deviation from Case 1.

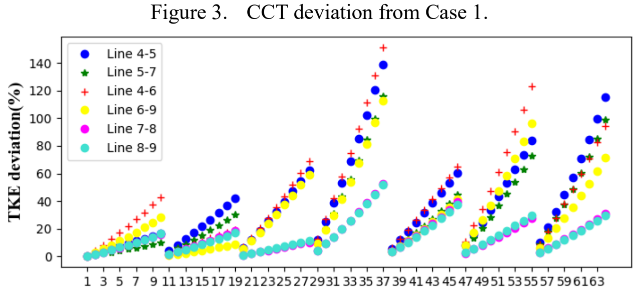

Figure 4. TKE deviation from Case 1.

To provide further details, the accelerating torque of SG3 for cases 20-28, when a fault is applied on line 4-5 is presented in Fig. 5 as a representative example. During the fault, the acceleration is higher as DER size increases, in line with what TKE behavior highlights. However, it should be noted that the deceleration area (as well as subsequent oscillations) can also be affected which can further affect the overall impact on transient stability. Similar behavior has also been observed in rotor angles.

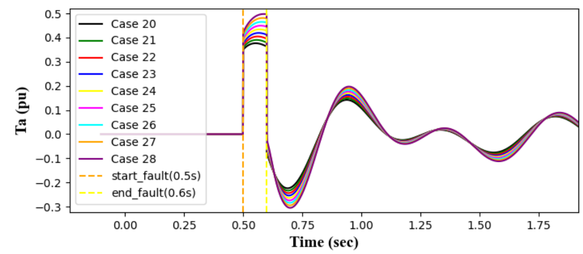

Figure 5. Accelerating Torque for SG3 for Cases 20-28. Fault on line 4-5.

B. Impact of variable initial conditions

The nine representative profiles are incorporated into the 9 Bus System and the two indices are calculated. The results considering each representative day are analyzed by means of boxplots, i.e., each boxplot includes all CCTs (or TKEs respectively) calculated for each day. The comparison concerns the case where the dynamic der_a model is considered (referred to as gross load+der_a in the presented results) and the case where only the net load is taken into account (referred to as net load). Therefore, in both cases, the total load seen at the transmission level is the same but in the latter the dynamics of the DERs, and the associated tripping effects, are neglected. Scenarios are presented for year 2020 (average daily DER PLs ranging from 3.27% to 16%) and 2025 (average daily DER PLs ranging from 4.33% to 21%) based on data and projections from [2], [11].

From all studies performed the results showed that the dynamic effect of DERs has a small impact on the examined indices for the profiles with small PLs, while higher PLs lead to more prominent changes in the percentiles and outliers. Considering longer duration faults, in most cases, the calculation of CCT is more optimistic without considering the der_a model and consequently DER dynamics. However, when the fault is located on line 8-9 and 7-8, which are the closest locations to DER-C, the opposite effect is observed but to a much lower extent. This reveals that the distance between the fault location and the DER unit which is the closest to the CSG can lead to opposing effects on transient stability. However, when it comes to shorter faults these opposing trends are not observed and TKE is lower for all fault locations, without the der_a consideration.

Due to space limitations, only two indicative fault locations are depicted, regarding faults on lines 4-5 (Fig. 6), which is far from the CSG and 8-9 (Fig. 7), which is the closest location to CSG. The green and dark blue boxplots correspond to the net load and gross load+der_a approach for all 9 representative profiles of 2020 (described in Section II.B), respectively. In a similar way the boxplots for 2025 are presented in yellow and light blue, for one indicative profile. In Fig. 6 all percentiles and outliers are lower when the der_a model is included, indicating deterioration in the CCT, (the maximum is the same since fault durations higher than 0.7 s were not considered as described in Section II), while the opposite trend appears in Fig. 7. Considering the impact of PL, the 2020 coldest day which has the smallest daily PL, shows almost identical percentiles for the two modelling approaches while bigger variations appear to the rest of profiles. The 2025 highest load day is also included in the figures to compare with the corresponding 2020 profile, which has lower PL. It can be observed that for the 2025 profile higher deviations between the percentiles of the two approaches appear, especially for line 4-5. It is important to note that the minimum CCT value, which represents the worst-case scenario, and can be used by system operators to assess transient stability, can be affected both positively (up to 4%) and negatively (up to 8%) if DER dynamics are included. Additionally, the medians can be underestimated to an extent of 12% and overestimated by 4%.

Regarding short-term faults the results are consistent throughout all days and only one representative example of TKE is presented in Fig. 8, for the 2025 highest load day. It is observed that all percentiles are higher when the der_a is considered indicating a more consistent effect on the acceleration area captured by TKE.

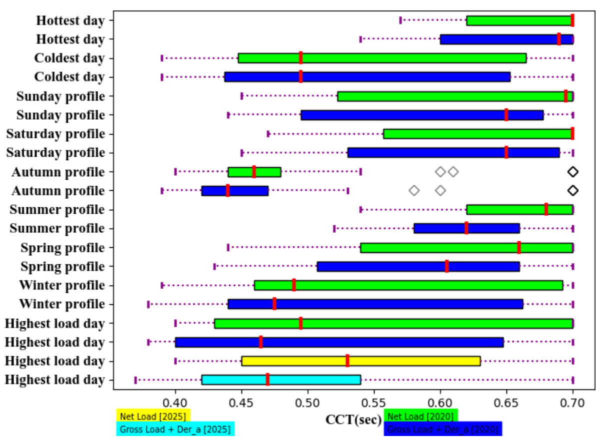

Figure 6. CCT Boxplots for fault on Line 4-5.

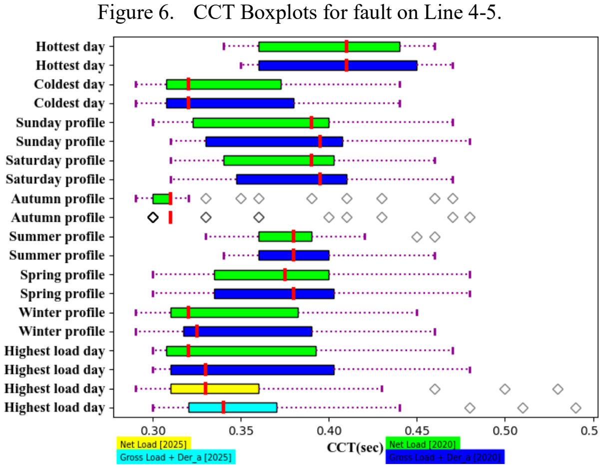

Figure 7. CCT Boxplots for fault on Line 8-9.

V. Conclusions

In this paper, the impact of ADNs on transient stability is investigated and the extent to which neglecting DER dynamic

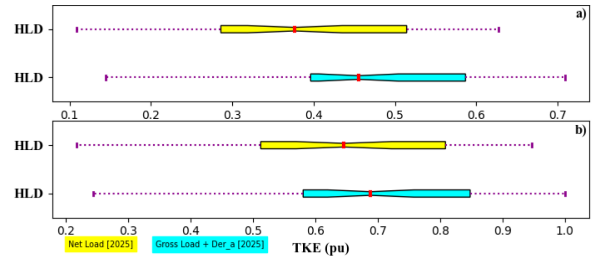

Figure 8. TKE Boxplots for fault on a) Line 4-5 and b) Line 8-9.

behavior can lead to over- or under- estimation of transient stability indices. Two main aspects are studied that focus on investigating the impact of the dynamic behavior of DERs as well as the impact of the variability of operating conditions through the use of representative load and DER profiles. In addition, investigation related to locational aspects and fault duration is performed. Results from the application on the 9 Bus System reveal that the impact on transient stability is not always straightforward and can be positive in some cases and negative in others, leading to the possibility of both under- and over- estimation of transient stability indices if the dynamic behavior of DERs is neglected. Identifying the impact of control parameters and DER units trip settings through sensitivity studies is a further research direction of interest, since the dynamic behaviour of ADNs during and right after the fault can affect transient stability as seen in our studies.

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