Revisiting the Tripping Logic of the DER_A Model for Power System Stability Studies

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***Abstract*—The increasing amount of Distributed Energy Resources (DERs) in Distribution Networks (DNs) has awakened the interest of system operators to represent how DERs will react to large disturbances. These units will respond according to the ride-through capability curves, the tripping logic settings, the local voltage magnitude, and frequency measurements.**

In this paper, we show the limitations of the well-known DER_A model and propose changes to represent better the ride-through capabilities and the tripping of a population of DER units. We also show the need for more than one aggregation in the same bus to represent the response of the old and modern DER technologies.

To validate the new model, we run dynamic simulations of a Transmission Network (TN) and DNs with hundreds of DER units modeled in detail. The simulation results show that the proposed changes improve the representation of a population of DERs during low-voltage and low-frequency events.

***Index Terms*—DER, dynamic simulation, models, ride-through, tripping.**

I. INTRODUCTION

The energy transition of most countries to combat climate change has boosted the integration of renewable energy sources in power systems, including DERs. These are medium to small-scale electric power sources not directly connected to the bulk power system [1]. The increasing installed DER capacity, especially inverter-interfaced distributed generators, has motivated different studies regarding their impact [2], for example, to analyse the impact of DERs in TNs [3].

The TN operators are searching for efficient ways to represent the behaviour of DERs during large disturbances without explicitly modelling them or the voltage level they are connected to. This necessity has led to the development of aggregate DER models in the last decade, such as the discontinued PVD1 model [4] or the DER_A model currently used in North America [5]. The latter is subject to continuous review and improvements as the proportion of legacy DERs connected in the system reduces compared to that of modern DERs with more strict Ride-Through (RT) requirements, compliant with the Institute of Electrical and Electronics Engineers (IEEE) Std. 1547-2018 [1].

A realistic representation of DERs in power system stability studies is crucial for preventing massive disconnections of DERs triggered by large disturbances, which could result in further voltage and frequency problems. The latest version of the DER_A model uses a simple representation of the temporary and permanent disconnection of hundreds or thousands of DER units in the distribution system due to voltage and frequency events. Issues with this implementation were originally reported in [6].

In this paper, combined simulations of TNs and DNs subject to large disturbances are run to show that the latest version of the DER_A model may not effectively represent the tripping of small-scale DER units dispersed in the DNs. Because of this, several changes in the DER_A model are proposed. The modified DER_A model, called DER_A_RT, includes a more sophisticated tripping logic that emulates the Voltage Ride-Through (VRT) and Frequency Ride-Through (FRT) characteristics defined in IEEE Std. 1547-2018.

The remainder of this paper is organized as follows: The RT characteristics defined in the IEEE standard are summarised in Section II. An explanation of the DER_A model and its limitations is presented in Section III. The proposed modifications to the aggregate model are presented in Section IV, while the simulations used to compare the RT and trip representations are presented in Section V. Finally, the conclusion are drawn in Section VI.

II. IEEE STANDARD 1547

The IEEE developed the 1547 standard to address the challenges of integrating DERs to the Electric Power System (EPS). This standard focuses on the technical specifications that DERs must have to interconnect with the EPS, establishing requirements of performance, operation, testing, safety considerations, and maintenance [1].

In its first version, IEEE Std. 1547-2003 [7], the standard prescribes the response to EPS abnormal conditions by defining voltage and frequency thresholds at which the DER must cease to energise, given a specific duration. This is depicted in Fig. 1. The latest version of the standard, IEEE Std. 1547-2018 [1], requires better performance on the DERs connected to DNs.

New capabilities were defined to align the DER requirements with the reliability requirements of the EPS, also

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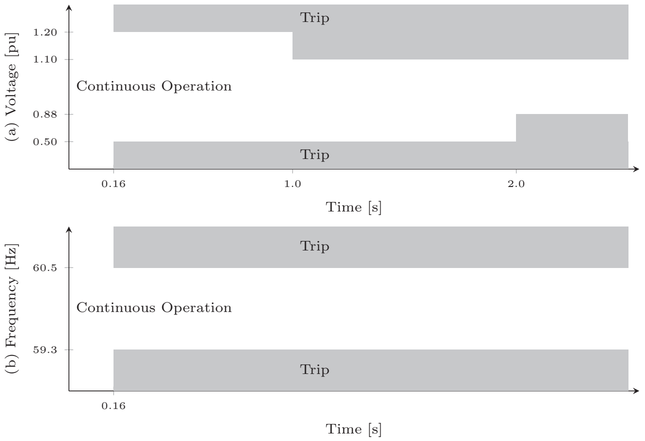

Fig. 1. Trip characteristics of IEEE Std. 1547-2003 for (a) voltage and (b) frequency.

searching for an improvement of reliability with the increasing DER penetration [8]. The new capabilities include the RT characteristics, which sustain the availability of the DER under abnormal conditions. For this, the standard defined the following three categories of DERs [8]:

- **Category I**: It is derived from the German guide BDEW for synchronous generators, so it considers the limitations of this type of generation. Most commonly-used DERs can achieve this RT definition, but the RT performance is inconsistent with the reliability standards imposed by the EPS. High DER penetrations that only follow this category could be detrimental to the EPS reliability.
- **Category II**: It covers minimum EPS reliability needs. The performance capabilities are attainable by inverter-based resources and possibly other DER technologies. The IEEE working group of Std. 1547-2018 expects this category to have the most widespread adoption.
- **Category III**: It is based on California Rule 21 and Hawaii's Rule 14H. It provides the longest duration and the widest band for RT capability and can be achieved by inverter-based systems. The standard was amended in [9] to provide more flexibility to this category, as power-distribution engineers deemed the low-voltage trip times to be very long in the original version.

The trip and RT requirements specified for each category are shown in Fig. 2. The requirements for voltage conditions vary by category, while those for frequency remain constant across all categories. The explanation used by [1] for the voltage trip requirements is as follows: when any applicable voltage is less than an undervoltage threshold, or greater than an overvoltage threshold, the DER shall cease to energise the EPS and trip within the corresponding clearing time. The same explanation applies to frequency tripping requirements.

In the case of VRT and FRT, the standard defines different operating zones. When the voltage or frequency values are outside the RT operation region parameters (value and cumulative duration), requirements for continued operation (RT), or restoring output after the voltage disturbance, shall not apply [1]. The RT zones are defined as follows:

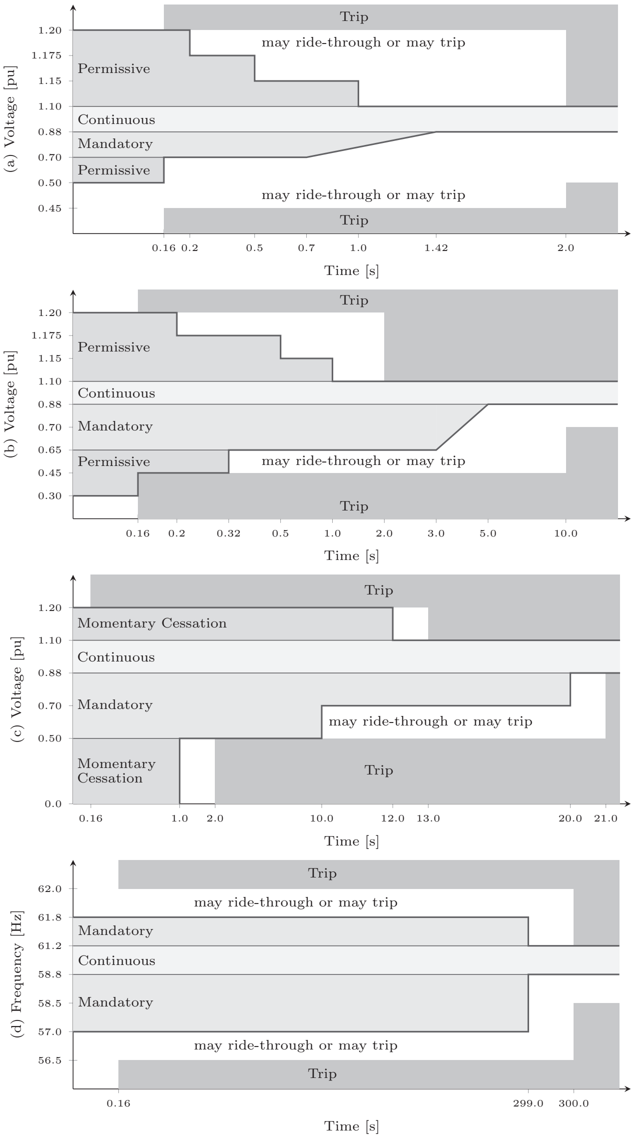

Fig. 2. RT characteristics minimum requirements for (a) Category I VRT, (b) Category II VRT, (c) Category III VRT, and (d) FRT of all categories.

- **Cease to energise**: Cease active power injection and limit the reactive power exchange. If the aggregate DER nameplate rating is less than $500\,\mathrm{kVA}$, the exchanged reactive power must be less than 10% of the nameplate DER rating. Otherwise, the exchanged reactive power must be less than 3% of the nameplate DER rating.
- **Momentary cessation**: Temporary cease to energise, in response to a disturbance, with the capability of immediately restoring the output when the voltage returns to the continuous or mandatory operation region.
- **Mandatory operation**: Required continuance of active current and reactive current exchange of DER with the EPS as prescribed, even in the presence of a disturbance in the EPS.
- **Permissive operation**: The DER performs RT either in mandatory operation or in momentary cessation, in response to a disturbance.

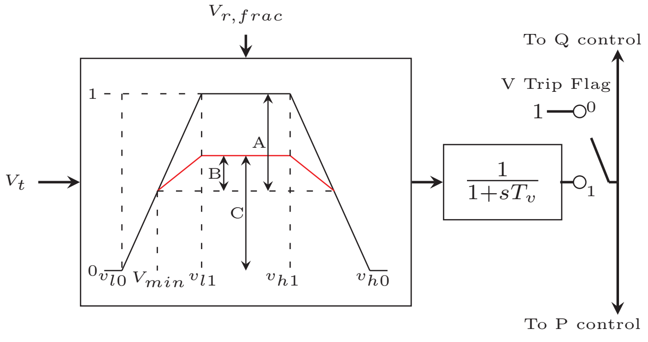

Fig. 3. Fractional tripping block in DER_A.

- **Continuous operation**: Exchange of current between the DER and an EPS within prescribed behaviour.

III. DER_A MODEL

The DER_A is a model that represents the aggregate behaviour of many small-scale, distributed, inverter-based generators in positive-sequence stability studies [5]. This aggregate model was developed by the Western Electricity Coordinating Council (WECC) and is a reduced version of the second generation of generic models for large-scale renewable generators, with approximately one third of its parameters. Furthermore, this model has been tested and validated in various simulation software [10].

The DER_A consists basically of the following parts: a reactive power-voltage control loop, an active power-frequency control loop, a frequency tripping logic, an active-reactive current priority logic, a fractional tripping logic, and a voltage source representation. A detailed explanation of each of these parts can be found in [5], [6], [11].

A. Voltage and frequency tripping logic

To emulate the response of the DERs to abnormal conditions defined in the Std. 1547-2018, the DER_A model has a fractional tripping and frequency tripping logic. This logic tries to represent the voltage trip and VRT requirements defined in the standard. Also, this logic attempts to emulate the voltage diversity along a distribution network since DERs do not necessarily trip simultaneously.

A graphical representation of the fractional tripping block is presented in Fig. 3. This block defines two thresholds for undervoltages (v_{l1} and v_{l0}) and two for overvoltages (v_{h1} and v_{h0}), each one with its respective timer. These thresholds are connected by a black line representing the fraction of active DERs in the aggregation, considering the voltage drop along the distribution networks. Therefore, if the voltage is lower than v_{l1} or higher than v_{h1}, only a fraction of the DERs will inject power to the EPS, and if the voltage is lower than v_{l0} or higher than v_{h0}, all the aggregated DERs are inactive. The block also has an input $V_{r,frac}$, which is used to define the fraction of DERs that will remain active after the fault is cleared (typically those with a modern technology), resulting in the red line shown in Fig. 3.

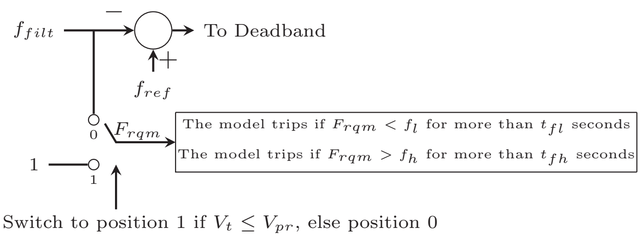

Fig. 4. Frequency tripping block in DER_A.

TABLE I
RECOMMENDED PARAMETER VALUES FOR DER_A TRIPPING LOGIC [11].

Parameter	IEEE 1547-2003	70% of 2003 30% of 2018	30% of 2003 70% of 2018	IEEE 1547-2018
v_{l0}	0.44 pu	0.44 pu	0.44 pu	0.44 pu
v_{l1}	0.49 pu	0.49 pu	0.49 pu	0.49 pu
v_{h0}	1.2 pu	1.2 pu	1.2 pu	1.2 pu
v_{h1}	1.15 pu	1.15 pu	1.15 pu	1.15 pu
t_{vl0}	0.16 s	0.16 s	0.16 s	0.16 s
t_{vl1}	0.16 s	0.16 s	0.16 s	0.16 s
t_{vh0}	0.16 s	0.16 s	0.16 s	0.16 s
t_{vh1}	0.16 s	0.16 s	0.16 s	0.16 s
$V_{r,frac}$	0	0.3	0.7	1.0
f_l	59.3 Hz	58.5 Hz	57.5 Hz	56.5 Hz
f_h	60.5 Hz	61 Hz	61.5 Hz	62 Hz
t_{fl}	0.16 s	0.16 s	0.16 s	0.16 s
t_{fh}	0.16 s	0.16 s	0.16 s	0.16 s

The frequency-tripping block incorporates the logic depicted in Fig. 4. This logic only has two thresholds, one for underfrequencies and another for overfrequencies. Also, each threshold has its own timer, which defines the seconds that the frequency can stay below f_l or above f_h. Since the frequency is a global variable, the entire DER_A model will trip if one the conditions shown in Fig. 4 is met.

For the parameter values of both tripping logics, reference [11] recommends using the values presented in Table I, which includes cases of mixed technology penetrations, i.e., penetration of both old and modern DER technologies.

Regarding the voltage threshold values, reference [11] explains that the Electrical Power Research Institute (EPRI) has demonstrated that a voltage drop of 5% along the distribution system is a reasonable value. This means that when the voltage at the substation busbar is at $0.49\,\text{pu}$, the voltage in DERs along the DN is probably at $0.44\,\text{pu}$, reaching one of the trip thresholds for Category II. For this reason, the value of v_{l1} ($0.49\,\text{pu}$) is $0.05\,\text{pu}$ greater than v_{l0} ($0.44\,\text{pu}$), using the Category II low voltage trip threshold value as v_{l0}. The same applies to v_{h1} ($1.15\,\text{pu}$) and v_{h0} ($1.2\,\text{pu}$).

In the case of the frequency threshold values, reference [11] recommends that, for mixed penetrations of old and modern DERs, the values of f_l and f_h fall within the range defined in the IEEE Std. 1547-2003 and Std. 1547-2018, depending on the penetration of each technology.

B. Issues found in the tripping logic of DER_A

In a previous work [6], the RT representation of the DER_A was compared with that of a population of DERs modeled in

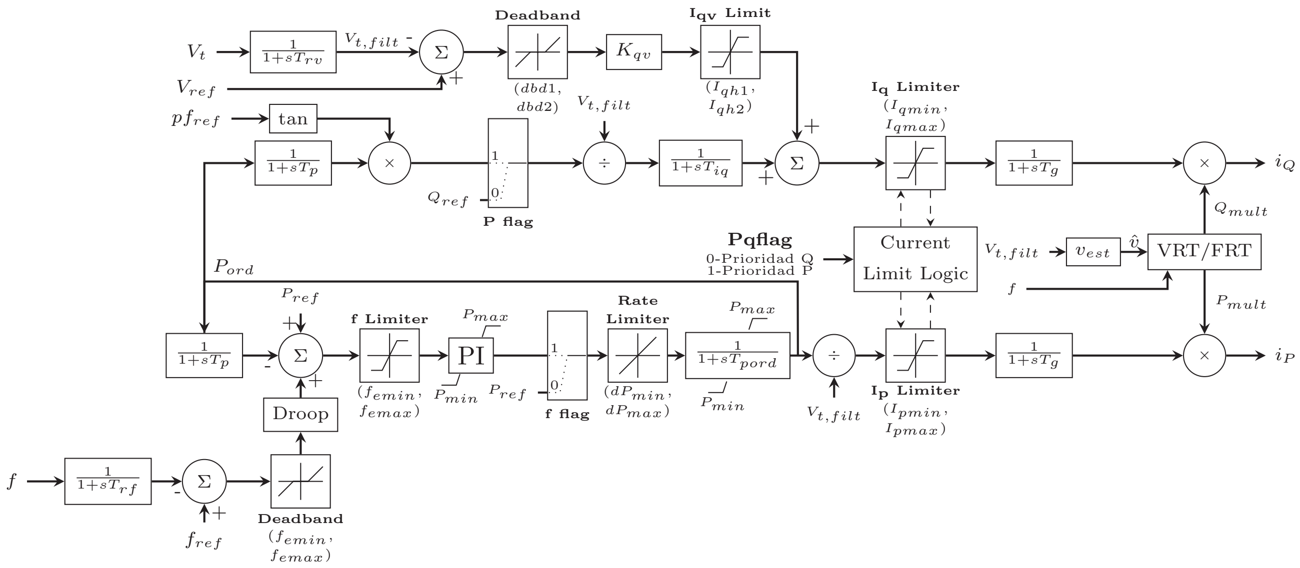

Fig. 5. DER_A_RT model block diagram.

detail by the so-called DER_D [12], using dynamic simulations. The DER_D is a model that represents a single small-scale DER unit located in the distribution network, meant to be embedded in Transmission-Distribution (T-D) simulations for transmission system studies.

In the comparison, it was found that the DER_A may not be capable, with its limited number of thresholds, of representing the RT capabilities of a mixed aggregation of DERs. For example, in the fractional-tripping logic the only adjustable thresholds are v_{l0} and v_{h0}, as v_{l1} and v_{h1} are used to represent the voltage drop along the distribution networks. With only two adjustable thresholds, it is impossible to represent all the RT zones defined in the IEEE Std. 1547-2018 (see Fig. 2).

The limited number of thresholds also affects the frequency-tripping logic. In [6], it was demonstrated that the way the thresholds are chosen in [11] to represent a mixed penetration of DERs leads to errors in the tripping of the DER aggregation. This results in inappropriate trips for underfrequencies in modern-technology DERs, because the configured trip threshold in the DER_A was higher than the one used by the individual DERs, or the no trip of the old DERs, as the trip threshold in DER_A was lower than the one used in this technology.

IV. PROPOSED AGGREGATE MODEL

To resolve the issues found in the tripping logic of the DER_A, a new logic that incorporates the characteristics defined by IEEE Std. 1547-2018 for RT and trip is proposed. As a result, a new aggregate model called DER_A_RT is obtained. The block diagram is presented in Fig. 5.

The main change compared to the DER_A model is that the fractional tripping and frequency tripping blocks are replaced by a single block called VRT/FRT. This block is responsible for placing the simulated aggregation of DERs in the states defined by the zones of IEEE Std. 1547-2018.

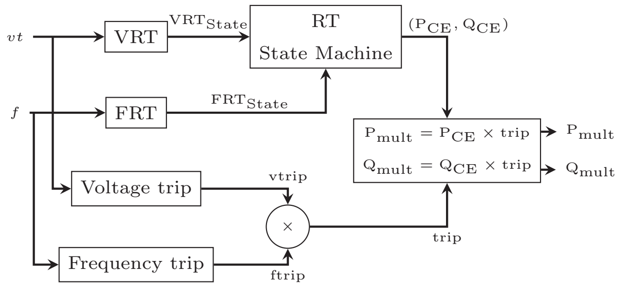

Fig. 6. General structure of the VRT/FRT block in DER_A_RT model.

The general structure used for the VRT/FRT block is shown in Fig. 6. First, the structure has the VRT and FRT blocks, directly implementing the RT curves presented in Fig. 5. To achieve this, the blocks use finite states machines to transition between zones and timers to define when to enter the “may ride-through or may trip” zone.

The timers are designed following the indications of [13], which is a standard that reviews the interconnection of inverter-based resources to the transmission system. In this standard, the time is taken per zone (each zone with its own timer), starting the timer when the voltage or frequency value enters the RT zone and stopping it when the value returns to the upper zone for low voltage or low frequency cases, or the lower zone for high voltage or frequency cases.

The outputs of the VRT and FRT blocks are the states in which their internal state machine is located. The possible states in the VRT block are: 1 for normal operation, 2 for high voltage cease, 3 for low voltage cease and 4 for the “may ride-through or may trip” zone. The FRT block has two states: 1 for normal operation and 2 for the “may ride-through or may trip” zone. The outputs from VRT and FRT are used in another state machine that defines the percentage of active

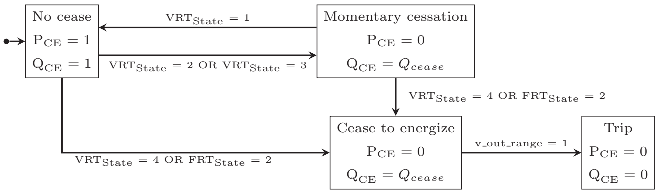

Fig. 7. RT State Machine used in the VRT/FRT block.

(P_{CE}) and reactive (Q_{CE}) power injected, relative to the power value during continuous operation, by the aggregate model.

The structure of this state machine is presented in Fig. 7. The state machine has a Q_{cease} variable to define the percentage of reactive power injected when the DERs are in cease mode, as defined in Section II. Also, it has a v_out_range parameter to select the aggregation behavior in the "may ride-through or may trip" zone.

Another group of state machines is used for the voltage and frequency tripping logic. In this case, there are only two possible states, 0 for trip and 1 for normal operation. The values of the voltage trip and frequency trip are multiplied and passed to another block that also receives the result given by the RT State Machine block. In this last block, a multiplication is performed to define the final output of the VRT/FRT block that is then used in the DER_A_RT model.

The proposed model incorporates a v_{est} block which contains a gain that multiplies the $V_{t,filt}$ signal and passes the result to the VRT/FRT block. This is done to approximate the voltage used in the RT to the terminal voltage seen by most of the individual DERs. In this paper, the $V_{t,filt}$ signal is multiplied by the average voltage magnitude of the individual DERs. The average voltage is calculated by conducting multiple T-D simulations with the test system, obtaining the voltage magnitude of the DERs for different perturbations at different times, and applying linear regression to obtain the gain utilized in v_{est}. In future work, efforts will be made to improve how the voltage of individual DERs is estimated for this aggregate model.

The proposed model has 1.3 times the number of continuous states of the existing DER_A model and 1.4 times the number of discrete variables. In addition, for simulating a mix of vintage and modern technologies, one requires connecting in parallel two instances of the new DER model instead of one.

Finally, the main limitation of this model is that the voltage estimation requires some prior knowledge of the voltage diversity across the distribution network. The proposed model also inherits from the existing DER_A other limitations not pertaining to the ride-through/tripping logic, such as simplified modeling of the power converter, predefined voltage- and frequency-control modes, and suitability only for RMS dynamic simulations (i.e., using the phasor approximation).

V. SIMULATIONS RESULTS

The simulations were carried out in RAMSES, a time-domain power system simulator [14], using the 50 Hz test system of Fig. 8. The two aggregate DER models are connected to bus 47 and they inject a total of 2 MW. The main purpose of these simulations is to highlight the issues of the DER_A model and verify if these are addressed by incorporating the improvements proposed in Section IV.

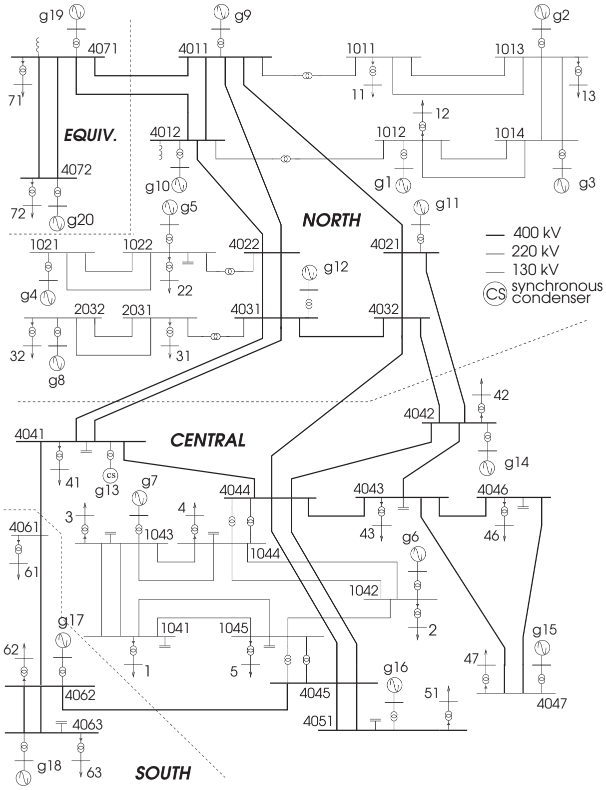

Fig. 8. One-line diagram of the TN [16].

Detailed T-D simulations are carried out to compare the response of the individual DERs against the aggregate DER_A and DER_A_RT models. To accomplish this, the detailed model DER_D is used [12], which represents small-scale DERs in the low voltage (LV) network. The individual units are located in DNs generated with the method explained in [15], where aggregate loads and generators are disaggregated into several DNs. The number of individual DERs that result after the disaggregation is 1160.

In the test system, 60% of the DERs are of modern technology, following IEEE Std. 1547-2018. The other 40% consists of vintage technology, following IEEE Std. 1547-2003. The modern technology is represented as DERs of Category II, because IEEE expects this category to be the most adopted. To represent this mix of technologies in the new model DER_A_RT, two aggregations are used in bus 47. This is not done for DER_A, since the model already attempts to consider the presence of both types of technologies.

In the simulations, the DER_A_RT and DER_D models use the VRT and voltage trip characteristics of Fig. 1 and Fig. 2, while the DER_A uses the values from Table I (adapting the values to the penetration level of each technology). As the test system operates in 50 Hz, the frequency thresholds were converted from 60 Hz to 50 Hz (keeping the same pu values),

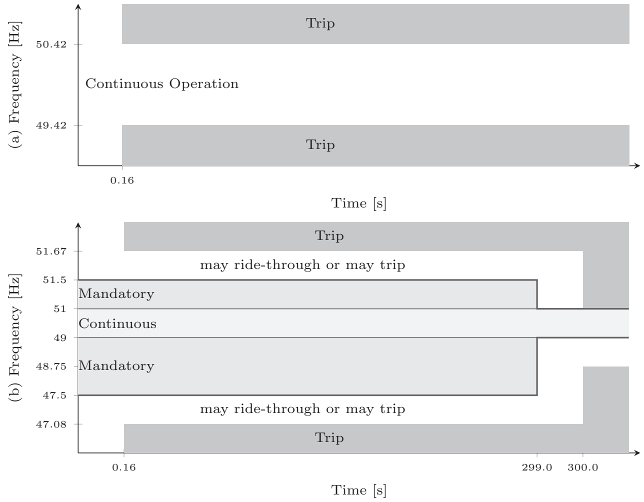

Fig. 9. Frequency characteristics of IEEE for (a) Std. 1547-2003 (b) Std. 1547-2018, based on 50 Hz.

resulting in the FRT and frequency trip characteristics of Fig. 9. In the case of the DER_A model, the parameters values are $f_l = 48.02\,\mathrm{Hz}$, $f_h = 51.17\,\mathrm{Hz}$ and $V_{r,frac} = 0.6$. The permissive operation zone is chosen as momentary cessation and the "may ride-through or may trip" zone is configured for cessation.

For the comparison between DERs models, three different cases are simulated. In the first two cases, the low VRT response is compared, while in the last case, a low FRT comparison is made.

A. Case 1

The applied disturbance is a three-phase short circuit near bus 4047 with $30\,\Omega$ fault impedance. This disturbance is cleared $100\,\mathrm{ms}$ later by opening the line 4043-4047. The results of the simulations are shown in Fig 10.

In Fig. 10 (a) the voltages of the DER models are shown. For the detailed models (DER_D), the maximum voltage (the DER unit closest to the substation), the minimum voltage (the DER unit furthest to the substation), and the average voltage among all DERs in the system are displayed. In the DER_A, the terminal voltage is plotted, while for the DER_A_RT, the estimated voltage used by the RT logic is plotted. By using this estimated voltage, a value close to the average voltage of individual DERs is obtained, improving the representation of their overall condition. However, there is a difference between the voltage estimated by DER_A_RT and the average voltage value when the disturbance is introduced, so there is room for improvement in the voltage estimation.

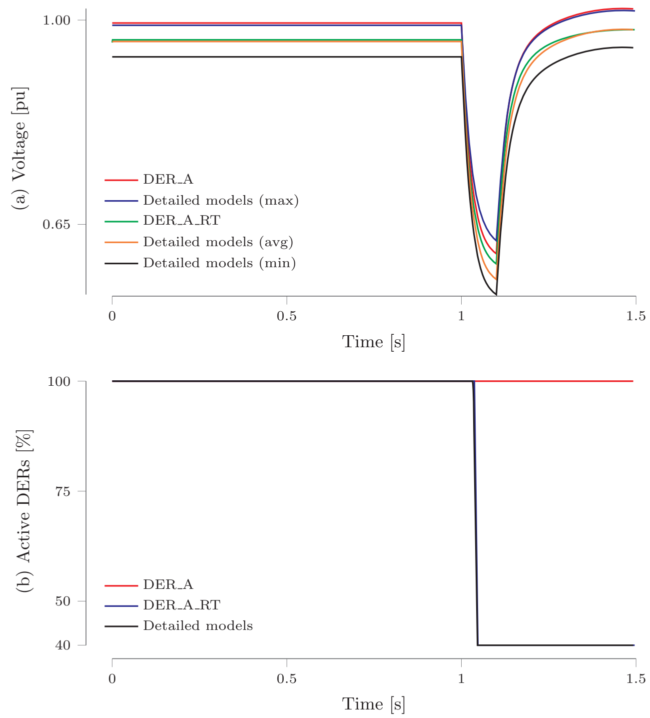

Fig. 10. Response to a three-phase short circuit near bus 4047 with $30\,\Omega$ fault impedance (Case 1).

TABLE II
PERCENTAGE OF ACTIVE DERS AFTER DISTURBANCE FOR DIFFERENT MIXES OF TECHNOLOGIES (CASE 1).

Percentage (modern / vintage)	DER_D (benchmark)	DER_A	DER_A_RT
50% / 50%	48.7%	100%	50%
60% / 40%	39.2%	100%	40%
70% / 30%	30.1%	100%	30%

Figure 10 (b) shows the percentage of DERs supplying active power to the grid (active units). It can be seen that only a 40% of the DERs remain active in the DER_A_RT and the detailed models (DER_D). The 60% that went inactive corresponds to the modern DERs, which enters the permissive operation region (configured as momentary cessation in Category II) when the voltage goes below $0.65\,\mathrm{pu}$. The voltage remains below $0.65\,\mathrm{pu}$ for more than $0.32\,\mathrm{s}$, causing the transition from momentary cessation to the "may ride-through or may trip" zone, which was configured for cessation.

The latter response does not happen in the DER_A, so that all DERs remain active. This occurs because the aggregate model has no way to represent all the RT thresholds required by the new standards, as explained in Section III-B, hence ignoring completely the cessation that occurred in the individual units. In this case, a better representation of the RT characteristics is achieved with the proposed model.

The same disturbance was applied with different mixes of modern and vintage technologies. The results of these simulations are summarized in Table II. Regardless of the mix, the simulations with the DER_A_RT model provide similar results to those with the detailed models.

B. Case 2

A similar disturbance is considered in Case 2, changing the impedance fault to $15\,\Omega$ and clearing the fault at $250\,\mathrm{ms}$.

The results are presented in Fig. 11. In this case, all the DERs went inactive due to the disturbance. In the DER_A_RT and DER_D, the modern units enter first the cease region, as

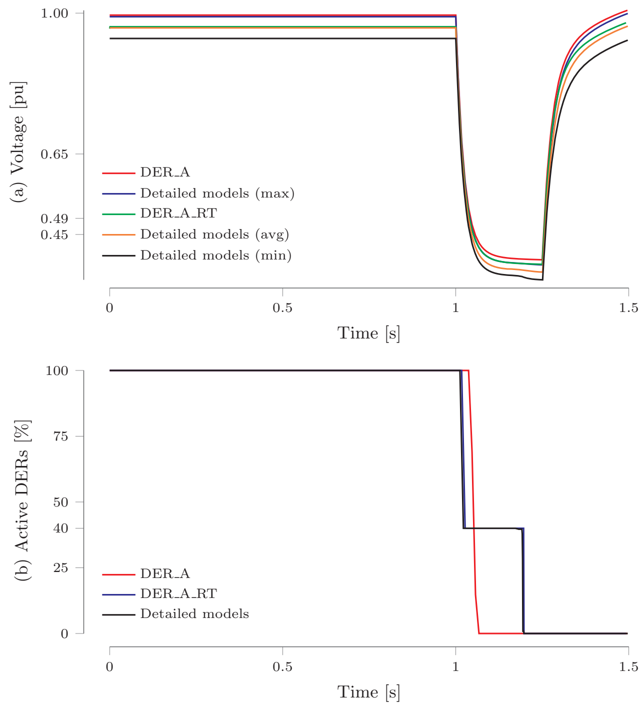

Fig. 11. Response to a three-phase short circuit near bus 4047 with $15\,\Omega$ fault impedance (Case 2).

in Case 1. After that, the old DERs trip because the voltage went under $0.50\,\mathrm{pu}$ for more than $0.16\,\mathrm{s}$. Meanwhile, the entire DER_A model trips before all the individual DERs went inactive. This happened because the voltage went under $0.44\,\mathrm{pu}$ (v_{l0}) for more than $0.16\,\mathrm{s}$. Similar to the first case, the DER_A_RT better represents the behaviour of individual units by fully modelling the RT and trip characteristics.

C. Case 3

For the last case, the loss of 40% of the power generated by unit $g20$ is simulated. This is done to compare the low frequency RT and tripping logic. Figure 12 shows the system frequency and active DERs when the disturbance is applied. In the figure, one of the issues explained in Section III-B is confirmed. In both DER_A_RT and detailed models there is a trip of vintage technology when the frequency went below the threshold $49.42\,\mathrm{Hz}$ for more than $0.16\,\mathrm{s}$ (see Fig. 9 (a)). This response is not seen in the DER_A model because the frequency never went below the f_l threshold, set to $48.02\,\mathrm{Hz}$, to take into account the mixed penetration, following the recommendation from [11].

VI. CONCLUSION

This paper proposes changes to the DER_A model currently used by system operators worldwide to represent aggregations of DERs units. The changes aim to improve the approximation of the ride-through and tripping of a population of DERs after large disturbances in the transmission system.

By comparing detailed versus aggregate representations of DER units, it was found that the DER_A model cannot represent all the RT thresholds defined by the IEEE Std. 1547-2018.

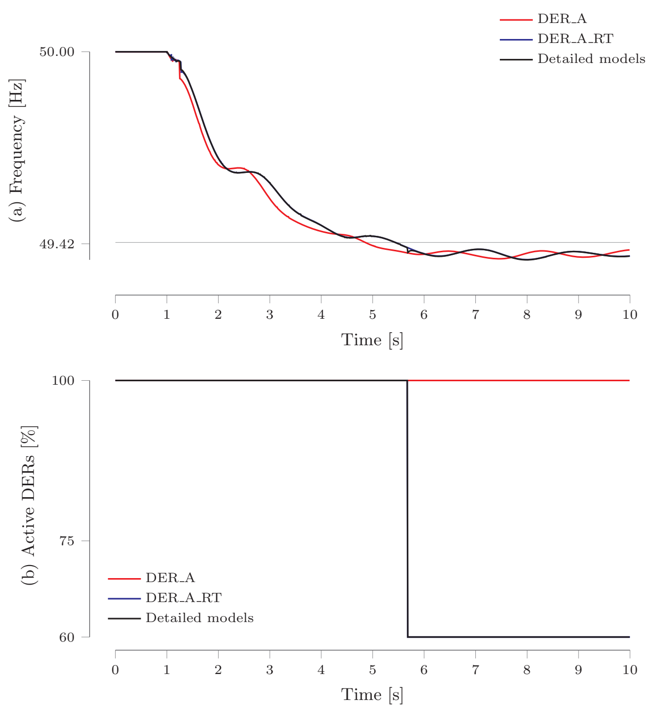

Fig. 12. Response to the loss of 40% of the power generated by unit $g20$ (Case 3).

This limitation is overcome with the proposed DER_A_RT model.

It was found that the DER_A model cannot represent the low-frequency trips in a mixed penetration of old and modern technologies with a single aggregation. Meanwhile, using the modifications proposed in Section IV in two separate aggregations gives a more accurate approximation of the individual DERs active state.

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