Aggregated Distributed Energy Resource Model Improvements and Validation: PV-MOD Milestone 2.7.7

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ABSTRACT

This report documents the proposed improvements for the aggregated DER_A model for representing the behavior of distributed energy resources for transmission studies during budget period two of the DOE PV-MOD research.

Keywords
Dynamics
EMT
IBR
Modeling
PV
Unintentional islanding detection

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1 INTRODUCTION

Background & Motivation

Solar PV and other Inverter-Based Resources (IBR) installations interconnecting at the bulk power system (BPS) and the distribution grid are increasing rapidly across North America. At present, the availability, scope, and validation of stability (RMS), electromagnetic transient (EMT), power quality (PQ), quasi-static time series (QSTS), and short-circuit models of IBR and distributed energy resources (DER) in commercial vendor tools vary. If available, many models in commercial tools have not been thoroughly validated against laboratory and grid measurements with respect to representation of advanced inverter functionalities (especially for DER), correct parameterization, and reliable behavior under weak system conditions. Also, many existing models have not been extended to represent new inverter control functions from various inverter vendors spanning transmission and distribution (T&D) systems. Efforts are needed to better understand and validate the IBR/DER dynamic impact on bulk system stability, T&D protection, and power quality.

DOE awarded EPRI along with NREL, Terabase Energy, and other project partners federal research and development funding for the project titled "Adaptive Protection and Validated MODels to Enable Deployment of High Penetrations of Solar PV (PV-MOD)" [1].

Project Overview

The objective of this project is to develop and validate high-fidelity models of solar PV facilities at all levels of the power system across all operational reliability time frames and integrate these models into the commercial software tools used by power system engineers to plan, operate, and protect transmission and distribution (T&D) systems. These validated models will enable utilities, vendors, and developers to confidently study high-penetration PV systems, inform reliability investment decisions, and design systems that leverage smart inverter capabilities. The project will demonstrate advanced application of these new models including automated assessment and design of adaptive distribution protection schemes. These protection schemes will be deployed and tested in high-penetration field applications and microgrids for ensuring the resilience of critical infrastructure and for maintaining grid safety and reliability in response to dynamically varying system configuration and operating conditions.

EPRI and partners are conducting the following activities to further the state of the art in modeling of high penetration PV systems: (1) use lab/field measurements and advanced T&D co-simulation to evaluate and revise existing and/or develop new models to represent PV behavior for system reliability assessments across all operational reliability timeframes; (2) validate all developed models against field measurement disturbances; (3) use EPRI's existing vendor engagement processes to transfer the new models to commercial tool model libraries; (4) exercise these models in a new automated adaptive protection analysis tool for protection system design and testing, and (5) field-demonstrate multiple utility system adaptive protection schemes that leverage smart inverter capabilities to support changing system conditions including resilient critical infrastructure microgrid/islanded systems. These are summarized in Figure 1-1.

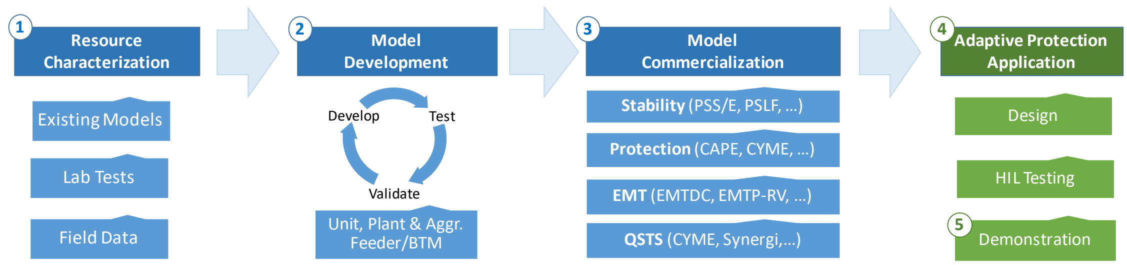

Figure 1-1
Proposed Technology Roadmap

Milestone 2.7.7 Overview

A state-of-the-art gap analysis of PV models was presented in milestone 1.4.1 [2]. Milestone 1.4.2 presented the PV and dynamic load modeling update with respect to generic models for stability, EMT, harmonics, and short circuit analyses from the first budget period of the PV-MOD project [3]. This milestone 2.7.7 report aims at improving *positive sequence models for aggregated feeders for bulk power system stability analysis* by developing and documenting preliminary or revised model specification, configuration, and validation in a dedicated report.

The DER_A model was released in 2019 [4] and since then, has been used for studies around the various power systems around the world. Based on learnings from extensive use and application of the model in multiple case studies [5], a few modifications and improvements are proposed in this document:

- Modifications to dynamic voltage support
- Representation of aggregate tripping due to unbalanced faults

Both improvements were proposed to software vendors at a WECC REMWG/MVS Meeting on May 16, 2022 [6].

As applicable, simulations have been performed with the proposed revised and adequately configured, demonstrating:

- the capability of the model to be configured to meet the IEEE 1547 performance requirements for active power and voltage control during continuous operating regions [4], and current injection in abnormal voltage operating region [5]
- capability to replicate a reasonable amount of the laboratory test results obtained in 2.6.2: replication of the behavior of individual solar PV inverter tests by the DER_A model may not be appropriate due to the *aggregate* characteristic of the model; this aggregated model is not intended to capture nuances of individual inverter behavior.
- capability to replicate a reasonable amount of the field data recordings from 1.2.2 and 2.2.1 [7]

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2
MODIFICATIONS TO DYNAMIC VOLTAGE SUPPORT

This section presents the model enhancements to the positive sequence transient stability models for aggregated Distributed Energy Resources (DER) used in bulk power system stability analysis. Although the contents of this Section was presented in the 1.4.2 report, it is retained here to maintain continuity.

DER_A voltage control loop

IEEE 1547-2018 Clause 6.4.2.7.2 states that the dynamic voltage support (DVS) should start when voltage leaves the continuous operating region (below 0.88pu) but should continue for 5 seconds after the voltage comes back into the continuous operating region. In the present implementation of dynamic voltage support in DER_A, the additional amount of current injected (Iqv) will go to zero as soon as the voltage error comes within the deadband and thus the DVS will not be continued for 5 seconds. Figure 2-1 shows the block diagram of the voltage control loop in the present DER_A model. Once the terminal voltage of DER_A is within the deadband the reactive current injection from the proportional control will fall to zero immediately. That is, if

$$V_{ref_0} - dbd2 \leq V_t \leq V_{ref_0} - dbd1$$

then $I_{qv} = 0$ since the control has gone into the deadband and thus *Verr* =0, which yields *Iqv* = 0 × *Kqv* = 0. Note that *dbd2* is always a positive number, while *dbd1* is always a negative number and although they are typically equal, they do not have to be. This means that the DER will attempt to regulate the voltage at its terminals by injecting (or absorbing) reactive current when the voltage drops (or rises) outside the deadband, but will immediately stop doing so once the voltage comes back within the deadband. Although, this may indeed be the way some DER might be designed, IEEE 1547-2018 Clause 6.4.2.7.2 states that once the voltage comes back within the continuous range (i.e., within the deadband) it should continue to control voltage for another 5 seconds.

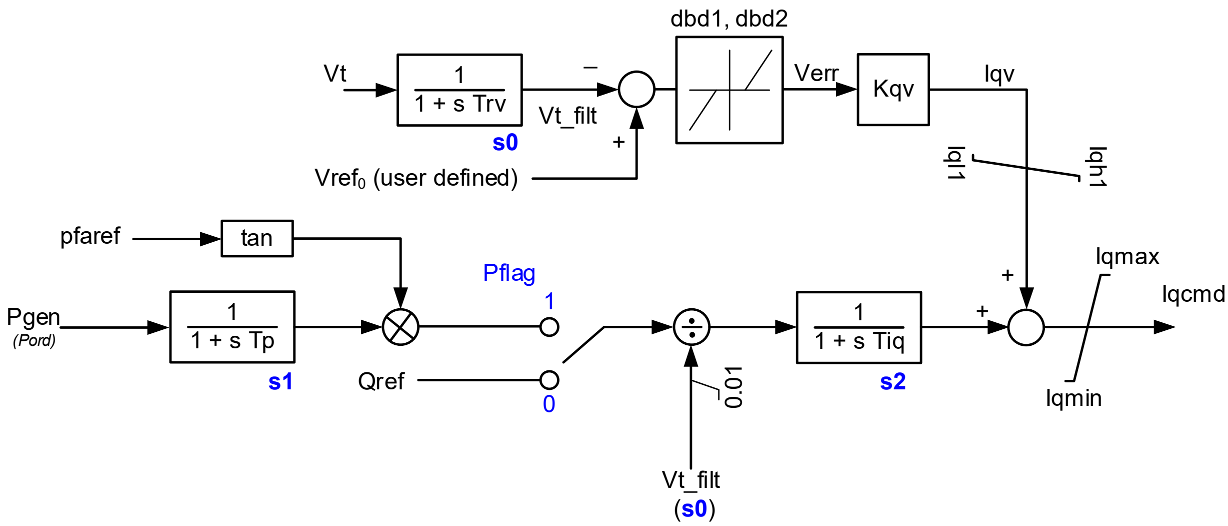

Figure 2-1: DER_A voltage control loop

Model Improvement

To allow for modeling a response as described in IEEE 1547-2018 Clause 6.4.2.7.2, the voltage control loop of DER_A can be modified to mimic the deadband voltage control loop used in the SVSMO3 [2] model shown in Figure 2-2.

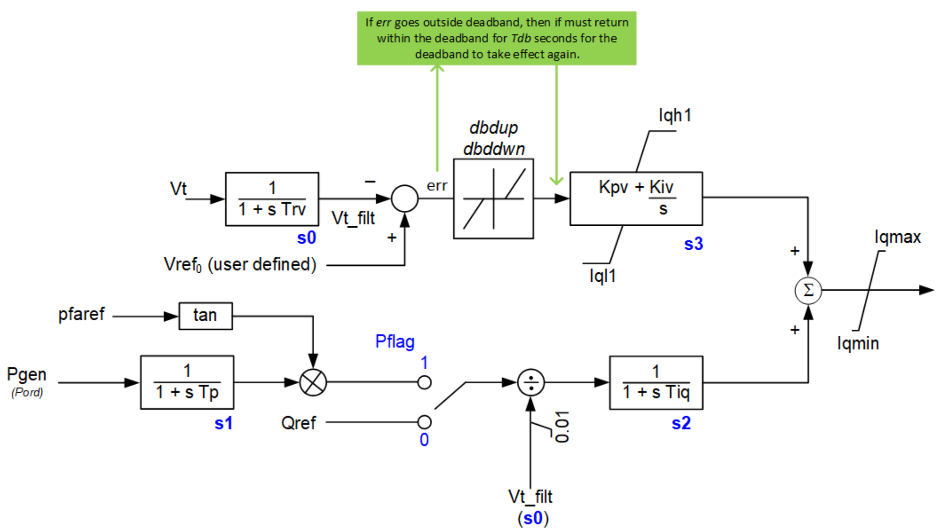

Figure 2-2: Proposed voltage control loop

Proposed pseudo code:

if ((*dbdup* ≠ 0) AND (*dbddwn* ≠ 0))
    Vup = Vrefo + dbdup
    Vdown = Vrefo + dbddwn
    if ((*Status* = 2) AND (*Vt* ≤ *Vup*) AND (*Vt* ≥ *Vdown*))
        err = 0 *(this forces ds3/dt = 0 as well)*
        s3 = Init_s3 or 0 or remove this statement (i.e. s3 freezes at its final value)
    elseif ((*Status* = 2) AND ((*Vt > Vup*) OR (*Vt < Vdown*)))
        Status = 0

```
        endif
        if (Status ≠ 2)
                if ( (Vt ≤ Vup) AND (Vt ≥ Vdown) )
                        if (Status = 0)
                                Status = 1
                                Timer = t (t is the current time in the simulation, e.g. dypar[0].time in GE PSLF™ or
                                        TIME in Siemens PTI PSS®E)
                        else
                                ΔT = t – Timer
                                if (ΔT ≥ Tdb)
                                        Status = 2
                                endif
                        endif
                else
                        if (Status = 1)
                                Status = 0
                                Timer = 99999
                        endif
                endif
        endif
endif
```

Notes:

- *Init_s3* = Initial Value of state *s3* at *t*=0 at the beginning of the simulation and set during initialization.
- *Status* = 2 and *Timer* = -99999 set during initialization.
- *dbdup* > 0 (e.g. 0.1 pu) and *dbddwn* < 0 (e.g. -0.1), thus allowing an asymmetrical deadband if desired; also upon initialization the user is warned and deadband disabled if inappropriate values entered for either or both these values (e.g. zero entered for either or both values), or if upon initialization *Vt* is outside of the deadband (i.e. *Vt* > *Vrefo* + *dbdup* or *Vt* < *Vrefo* + *dbddwn).* If *Vt* is outside of the deadband upon initialization, then *Vrefo* is set to *Vt* and model initialized and warning given to the user to this effect.

The logic is depicted in a diagrammatic way in Figure 2-3 together with an illustrative example of how the controls might act shown in Figure 2-4.

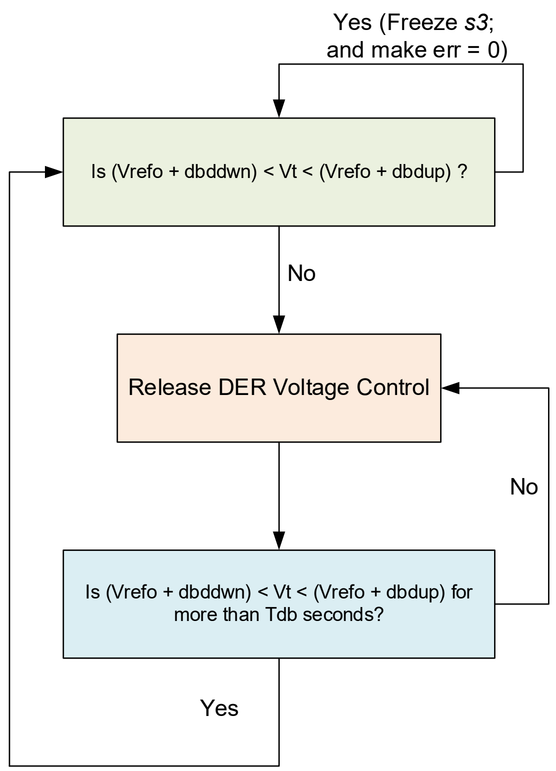

Figure 2-3: Proposed deadband similar to SVSMO3

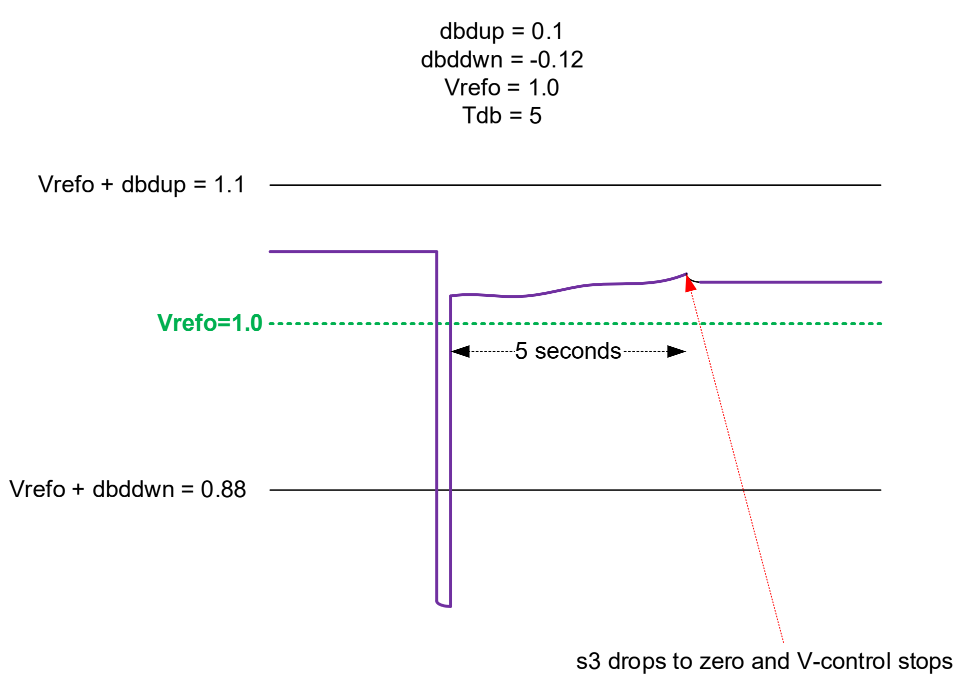

Figure 2-4: Expected response of proposed addition

As shown in Figure 2-2, the proportional controller acting on *Verr* in the existing DER_A model is changed to a PI controller and separated it from the constant-Q and constant-pf controls for increased flexibility.

Prototype testing

A simple single machine infinite bus setup has been used to illustrate the working of this concept. The system is as shown in Figure 6. The machine at bus 1 is assumed to an infinite bus of MVA rating 100 MVA while the DER is assumed to be connected at bus 20004. The source at bus 1 is represented by a round rotor synchronous generator model with a static excitation system.

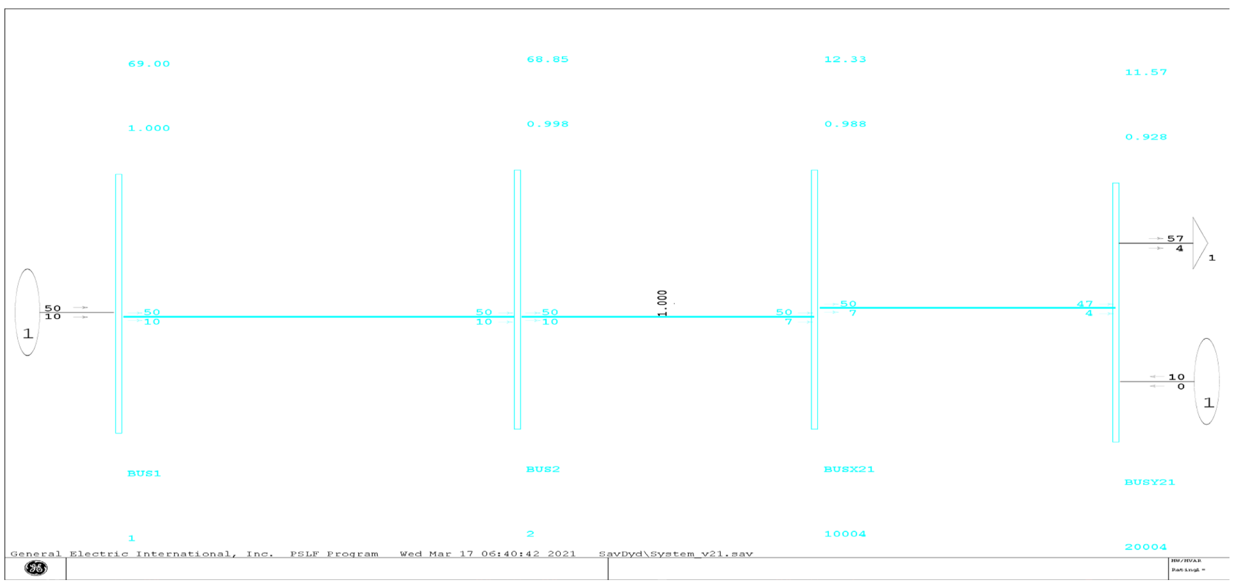

Figure 2-5: Single line diagram of test system

The model prototype has been implemented in a standalone user-written model in the GE-PSLF positive sequence simulation software platform. The initial values of various parameters are:

mva=15.0 “Xe” 0.15 “Imax” 1.1 “pqflag” 0 “Trv” 0.02 “Kpv” 20.0 “Kiv” 0.1 “Iqh1” 1.0 “Iql1” -1.0 “Tg” 0.02 “dbdup” 0.1 “dbddwn” -0.1 “Tiq” 0.02 “Tdb” 5.0 “rrpwr” 10.0 “Pflag” 0 “Iqh1” 99.0 “Iql1” -99.0 “Freq_flag” 0 “Pmax” 1.0 “Pmin” 0.0 “Tpord” 0.0

Since the objective is to illustrate the working of the dead band and associated control algorithm, the remaining features of DER_A (such as partial voltage trip logic and frequency response) have not been implemented in this prototype user defined model.

To illustrate the working of the model, a three-phase fault is applied midway on the line between bus 1 and bus 2. The fault is cleared in 6 cycles. Subsequent to fault clearing, the impedance of the line between bus 1 and bus 2 is increased from 0.1pu to 0.5pu to illustrate a weaker post fault network. The voltage magnitude at the terminal of the DER model is shown in Figure 2-6 while the value of Iqcmd is shown in Figure 2-7.

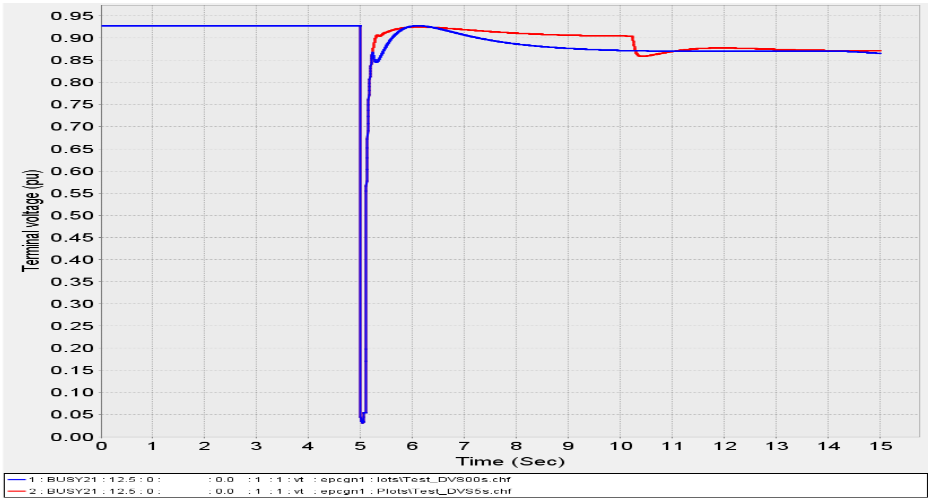

Figure 2-6: Voltage magnitude for two different values of Tdb (Blue - Tdb = 0.0s, Red - Tdb = 5.0s)

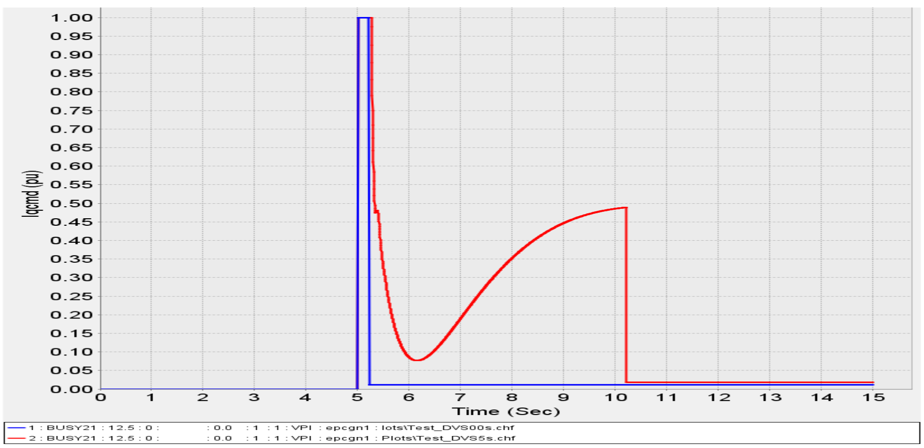

Figure 2-7: Reactive current command for two different values of Tdb (Blue - Tdb = 0.0s, Red - Tdb = 5.0s)

Outlook

The proposed modification to the DER_A model was presented to the WECC MVS in its May 2022 meeting and was taken into consideration.

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9. Generic Static Var System Models for WECC, April 18, 2011. https://www.wecc.org/Reliability/WECC-Static-Var-System-Modeling-Aug-2011.pdf

3
REPRESENTATION OF AGGREGATE DER TRIPPING TO UNBALANCED FAULTS

Positive sequence simulation platforms only have a limited ability to represent impacts due to unbalanced faults. However, with increase in percentage of distributed energy resources (DER), it may be beneficial to have a representation of behavior of these resources to unbalanced faults when conducting large system studies in positive sequence simulation environments. This is because depending on the transformer winding configuration at the distribution – transmission interface, a large number of single-phase DER could trip for unbalanced faults. If this tripping of single phase DER is not captured in transmission simulations, then the simulation results could portray an optimistic behavior of the system.

An explanation of the impact of transformer winding configuration on potential DER behavior can be obtained from the following example. In Figure 3-1, Bus 1 is 230kV, Bus 2/Bus 3 is 115kV, Bus 4/Bus 5 is 12.47kV. Transformer T1 is between Bus 1 and Bus 2 while transformer T2 is between Bus 3 and Bus 4. A variety of unbalanced faults were applied on Bus 1 and the voltage on Bus 5 (both the individual phase voltages and the positive sequence equivalent) was noted and tabulated as shown in Table 3-1. In addition, the voltages are tabulated for different values of fault impedances.

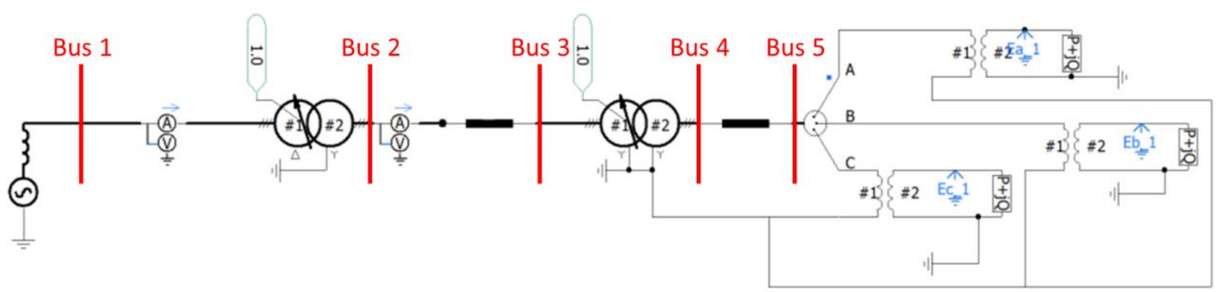

Figure 3-1: One-line diagram of network under study

As an example, for a solid L-L-G fault (Zf = 0) at Bus 1, when T1 winding is Δ(30)-Y configured and T2 winding is Y-Y configured, the on-fault voltage level on phase A at Bus 5 is 0.58pu, on phase B is 0.34pu, and on phase C is 0.57pu. Now, if all individual DER on the feeder have a trip threshold of 0.5pu, then we can safely assume that all single phase DER connected on phase B would trip (hence the pink color). On phases A and C some amount of single phase DER trips would occur, especially if the DER are located towards the middle or tail end of the feeder, and assuming that the voltage profile across the feeder uniformly decreases from substation towards the tail. Due to this uncertainty, the cells are highlighted in mild yellow color indicating that there will some amount of DER trips, but it would be difficult to generalize and quantify the exact amount. Finally, three phase DERs would also trip as the least voltage phase voltage (phase B) is below the trip threshold. Overall, for this fault, when viewed from the substation (either at Bus 3 or Bus 5), it can be assumed that more than 50% of the DER on the feeder would trip.

Now, if this fault was approximated in a positive sequence simulation platform, the positive sequence voltage observed at Bus 5 would be 0.497pu. If the DER_A model's voltage trip characteristic is parameterized to reflect tripping behavior due to unbalanced faults as detailed in [1] with the characteristic lying between 0.8pu and 0.6pu, then for this same unbalanced fault, DER_A model would reflect that all DER at the substation would trip (as indicated by the red color). This is of course a conservative representation because as reasoned previously, possibly only 50% of DER may trip. However, in such a scenario, a conservative representation may be alright for transmission system planning.

Another example scenario is for a L-L fault at Bus 1 with Zf = 0.2pu. If we assume that both T1 and T2 have windings with Y-Y configuration, then the individual phase voltages at Bus 5 are 0.95pu, 0.34pu, and 0.96pu respectively on phases A, B, and C. Here, again, all single phase DER connected on phase B will trip. However, single phase DERs connected on phases A and C would ride through the fault (denoted by the green color). All three phase DERs would also trip because of the low phase B voltage. Thus, we can assume that probably 30 – 50% of DER MW would trip. This scenario can be assumed to be a mild trip of DER.

When represented in a positive sequence platform, the positive sequence voltage at Bus 5 would be 0.75pu. Here, the DER_A model (if the voltage trip characteristic is parameterized as before to lie between 0.8pu and 0.6pu) would show a possible 20 – 30% trip of DER based on the 0.75pu positive sequence voltage. Thus again, for this unbalanced fault, the DER_A could possibly adequately reflect the trip of DERs from the requirement of transmission planning.

It must be kept in mind that the parameterization of the DER_A model's voltage trip characteristic to lie between 0.8pu to 0.6pu is to be used only to observe the performance under unbalanced faults. For three phase faults, the trip characteristic should lie between 0.55pu and 0.45pu as the trip threshold of an individual DER is assumed to be 0.5pu.

While this method and approximation may be adequate in most scenarios, it is definitely not 100% precise or accurate. As an example, consider the L-G fault at Bus 1 with Zf = 0.1pu. In this scenario, irrespective of the transformer winding configuration, two phases never see the chance of DER tripping, but one phase, could possiblly see DER tripping based upon the voltage profile across the feeder. Thus, there is a chance of about 10 – 30% of DER tripping. However, the equivalent positive sequence voltage is marginally above 0.8pu at the substation head. Here, if the DER_A model is placed right at the substation bus, then it possible that the DER_A model would suggest that all DER would be able to ride through the event. However, if the DER_A model is placed at the low end of an equivalent feeder, then the model may be able to represented a small percentage of DER tripping as the equivalent positive sequence voltage at the low end of the equivalent feeder would be lower than the equivalent positive sequence voltage at the high end of the equivalent feeder.

Table 3-1: Voltages at bus 5 for different scenarios of unbalanced faults and transformer winding connections

			T1/T2 Y-Y/Y-Y	T1/T2 Y-Y/Δ(30)-Y	T1/T2 Δ(30)-Y/Y-Y
Zf = 0	L-G at Bus 1	V_a	0.05	0.57	0.58
		V_b	0.95	0.56	0.56
		V_c	0.97	0.96	0.96
		V_+	0.656667	0.6966667	0.7
	L-L at Bus 1	V_a	0.55	0.85	0.85
		V_b	0.55	0.34	0.33
		V_c	0.97	0.85	0.85
		V_+	0.69	0.68	0.6766667
	L-L-G at Bus 1	V_a	0.29	0.58	0.58
		V_b	0.29	0.34	0.34
		V_c	0.96	0.58	0.57
		V_+	0.513333	0.5	0.4966667
Zf = 0.1pu (52.9Ω)	L-G at Bus 1	V_a	0.6	0.91	0.91
		V_b	0.96	0.54	0.54
		V_c	0.96	0.96	0.96
		V_+	0.84	0.8033333	0.8033333
	L-L at Bus 1	V_a	0.8	1.01	1
		V_b	0.28	0.37	0.37
		V_c	0.96	0.67	0.67
		V_+	0.68	0.6833333	0.68
	L-L-G at Bus 1	V_a	0.6	0.91	0.91
		V_b	0.6	0.61	0.61
		V_c	0.96	0.55	0.54
		V_+	0.72	0.69	0.6866667
Zf = 0.2pu (105.8Ω)	L-G at Bus 1	V_a	0.8	1	1
		V_b	0.96	0.72	0.72
		V_c	0.96	0.96	0.96
		V_+	0.906667	0.8933333	0.8933333
	L-L at Bus 1	V_a	0.95	1.09	1.09
		V_b	0.34	0.6	0.6
		V_c	0.96	0.6	0.6
		V_+	0.75	0.7633333	0.7633333
	L-L-G at Bus 1	V_a	0.84	1	1
		V_b	0.83	0.82	0.82
		V_c	0.96	0.75	0.75
		V_+	0.876667	0.8566667	0.8566667

Using this background, a modification to the DER_A model could be to add a parallel trip characteristic as shown in Figure 3-2. Here, the DER_A model can have two sets of partial trip characteristics, one for balanced faults and one for unbalanced faults. Further, simulation software (such as PSLF, PSS®E, TSAT, PowerWorld) can automatically enable the appropriate tripping characteristic to be used based on the type of fault applied during the study.

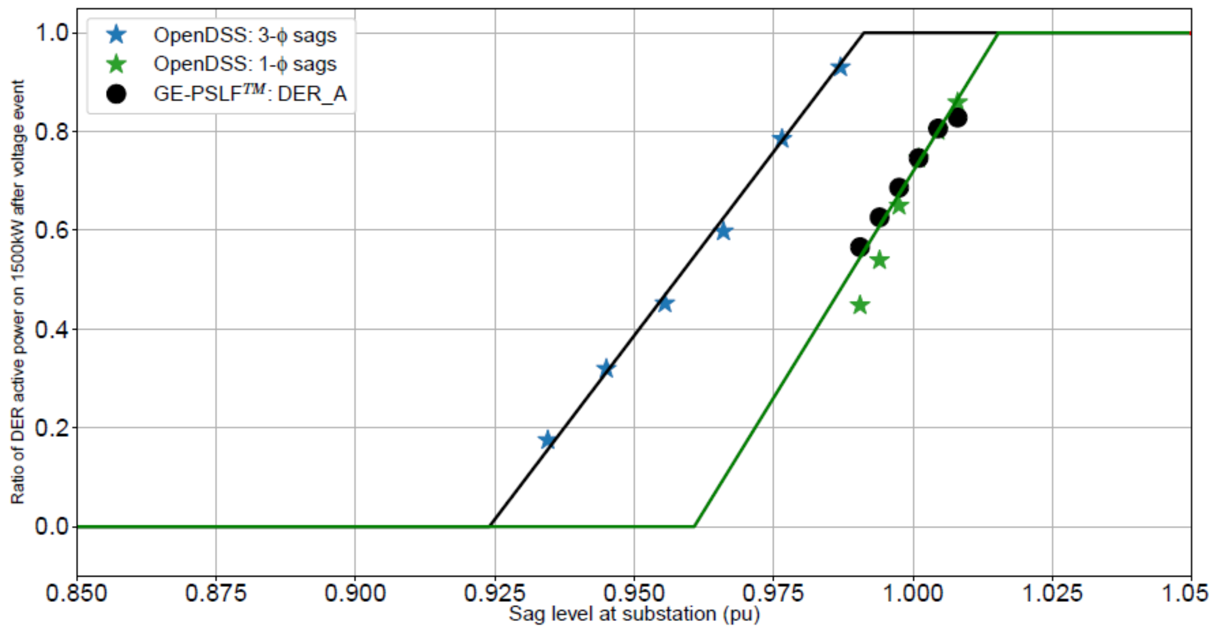

Figure 3-2: Representation of second partial trip charactersitic in DER_A model to approximate tripping of DER to unbalanced faults

4
SUMMARY AND OUTLOOK

This report proposed improvements to a *positive sequence model for aggregated feeders for bulk power system stability analysis* (DER_A) by developing and documenting preliminary or revised model specification, configuration, and validation in a dedicated report under the PV-MOD project. Based on learnings from extensive use and application of the DER_A model in multiple case studies, a few modifications and improvements were documented in this document:

- Modifications to dynamic voltage support
- Representation of aggregate tripping due to unbalanced faults

Future research intends to analyze and resolve, at least, the following potential DER_A model gaps that were identified in milestone 1.4.1.

- Representation of active anti-islanding scheme in an aggregate DER model

Other potential gaps in the DER_A model may be, in descending order of priority:

- Representation of vector-shift (phase jump) and RoCoF (loss of mains) ride through/trip functionality
- Representation of trip versus momentary cessation in the same model instance
- Representation of voltage trip without momentary cessation or blocking of inverters for low voltage.
- Possible gap for long term voltage stability margin representation with DERs and unbalance in distribution system
- Representation of negative sequence current contribution
- Representation of partial frequency trip characteristics[1]
- Representation of BTM rooftop and energy storage in the same instance of the model

The response of the DER_A model within transmission networks with very high instantaneous penetration (up to 100% of instantaneous load) of inverter-based resources has been presented in the following public reports of PV-MOD supported research:

- *Applicability of T&D Co-Simulation for Accurate Capture of Load and DER Dynamic Behavior.* EPRI, Palo Alto, CA: 2021. 3002021940.

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[1] At an April 2020 WECC MVS meeting, based on an EPRI presentation, it was decided that at the moment there is no need to implement partial frequency trip logic. Rather, it could be easier to staged frequency trip relays.

- *Applicability of T&D Co-Simulation for Accurate Capture of Load and DER Dynamic Behavior.* EPRI, Palo Alto, CA: 2020. 3002019452.

As for potential improvements of the DER_A model for weak grid analyses, research to date has not indicated a practical scenario where the short circuit strength (SCR) at the distribution substation is smaller than 10. Future research may address this topic at the appropriate time.

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Milestone 1.4.2 report for DOE

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