Power System Dynamic Contingency Analysis with Adaptive Distribution System Modeling

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***Abstract*—The integration of distributed energy resources, power electronics, dynamic and nonlinear loads into distribution systems introduce unique dynamic behaviors. Distribution systems are generally aggregated as loads in transmission-level dynamic studies, but this approach fails to model voltage differences along a feeder line. Hence, they cannot accurately capture these grid edge devices' voltage-sensitive dynamic characteristics, especially in the periphery region of a contingency. Yet, modeling all distribution systems in full detail via a transmission and distribution co-simulation introduces excessive computational complexity. To address this problem, this paper proposes an adaptive distribution system modeling method for bulk power system dynamic contingency analysis. First, a short-circuit analysis based screening method is developed, efficiently identifying regions suitable for different modeling fidelity due to a fault contingency. Then an existing T&D dynamic simulation engine is extended to perform adaptive dynamic contingency analysis, subject to these regions. Test results on the IEEE 300-bus system show the proposed method reduces computational time by 83% while achieving 99.7% accuracy compared to the fully detailed modeling approach.**

***Index Terms*—transmission and distribution co-simulation, short-circuit analysis, dynamic contingency analysis**

I. Introduction

In recent years, the structure of bulk power systems has been changing. Decentralization of power generation is increasing with distributed energy resources (DERs), and power electronic loads are becoming more and more dominant in load composition. This transformation and modernization of the grid brings new engineering challenges along with it. A smaller amount of large synchronous generators and larger amount of DERs introduce stronger coupling and network interactions between transmission and distribution systems that have not been previously seen. Additionally, single phase air-conditioning motor loads can delay voltage recovery and have unique fault ride through behaviors [1]. Recent studies such as [1] and [2] showed that typical aggregation of distribution systems as single or composite loads combined with using positive sequence simulation tools in in the transmission-level dynamic studies may result in notable simulation errors and hence system reliability risks. The main reasons are (i) dynamic behaviors of these DERs and loads are voltage-sensitive when terminal voltages are below certain thresholds due to fault-ride-through and protection settings; (ii) Voltage differences along distribution feeders can be amplified due to motor stalling and delayed voltage recovery. Thus, accurately modeling the dynamic response of DERs in the periphery region (annulus) of a voltage sag was recommended by North American Electricity Reliability Corporation (NERC) [3].

However, depending on the selected distribution system topology, modeling bulk systems with distribution system disaggregation could add tens to hundreds of times more buses than in a transmission-only system. For dynamic contingency analysis, especially in real-time operation, this makes most simulations far too computationally complex for a transmission and distribution (T&D) co-simulation to be implemented (with both systems modeled with high-fidelity). For this reason, many utilities have not adopted modeling of distribution system in a disaggregated or highly detailed manner, even though it is and will increasingly be crucial in the future [4].

Therefore, a computationally efficient T&D co-simulation tool for dynamic contingency analysis is vital for modern power grid studies. This paper addresses this gap by developing a novel simulation method which adaptively models distribution systems in the periphery region of a voltage sag or fault in a highly detail manner, while aggregating distribution systems elsewhere as composite loads. This selective distribution system modeling approach is adjusted for each contingency in an automated fashion, paving the way for ultra-large-scale power grid studies.

The rest of this paper is organized as follows. The fundamentals and basic concepts of short-circuit analysis and dynamic contingency analysis are covered in Section II-A. Then, the proposed method of adaptive T&D co-simulation modeling is introduced in Section II-B and Section II-C. In Section III, the IEEE 39 and 300 bus systems are used to examine the effectiveness of the proposed method. Lastly, the conclusions are presented in Section IV.

II. Dynamic Contingency Analysis with Adaptive Distribution System Modeling

Dynamic contingency analysis is a critical part of power system studies, used to evaluate the system's behavior and stability under a range of potential disturbances, such as faults, line outages, or generator trips. Unlike static contingency analysis, which focuses on steady-state conditions, dynamic

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analysis simulates the time-dependent response of the power system, capturing the interaction of generators, loads, and control systems over seconds and/or minutes following a disturbance.

A. T&D co-simulation for dynamic contingency analysis

There are varying ways in which a dynamic simulation is conducted for dynamic contingency analysis. One of the main methods is the partitioned approach, where a set of differential equations are solved through numerical integration, alongside a set of nonlinear algebraic equations which are solved iteratively (known as the network solution) [5]. Generally, the whole simulation/system is solved in a singular, uniformly modeled manner. A co-simulation differs from this, as distribution systems are solved alongside the transmission system in a separated fashion. Methods for co-simulation have been a large topic of recent research, as the different representations of distribution and transmission systems introduce challenges in boundary conflicts. One method to handle this is the Multi-Area Thevenin Equivalent (MATE) approach [6]. Through the theory of superposition, the bus voltages can be found via:

$$V_i = V_{int,i} + V_{ext,i}$$

Where $V_{int,i}$ is the voltage at bus i due to *only* internal sources of the subsystem, $V_{ext,i}$ is the voltage at bus i due to the influence of exterior subsystems *only*, and V_i is the final realized bus voltage. The voltages due to exterior subsystems are computed through the link branches connecting all subsystems, with each system represented by a thevenin equivalent. More information on the MATE approach can be found in [6]. InterPSS utilizes this framework, and is chosen as the dynamic simulation tool for this study.

B. Identification of Detailed Distribution Modeling Regions Using Short Circuit Analysis

While a T&D co-simulation provides an opportunity for dynamic distribution system effects to be displayed, it is exceptionally exhaustive, computationally. It is desirable to develop an adaptive modeling approach to manage the overall computational complexity. This study accomplishes this through a voltage estimation of the system, in anticipation of a fault as a disturbance.

As discussed earlier in the introduction, dynamic behaviors of DERs, motors and electronic loads are highly voltage-sensitive. For example, IEEE 1547 [7] declares that all new DERs shall be equipped with voltage/reactive power control, meaning DERs will inject reactive power based off point of common-coupling voltage. Furthermore, voltage-ride-through behaviors are not only strictly voltage magnitude dependent, but also dependent on voltage magnitude over a time threshold. Additionally, motor stalling is a common issue with single and three phase induction motor loads, which occur when terminal voltages drop below a certain threshold (e.g., 0.5-0.6 pu).

For the reasons mentioned above, bus voltage magnitude during a fault contingency is an ideal metric for estimating the excitation of dynamic behaviors from these devices. It follows that the detailed modeling of distribution feeders will be crucial in areas of high voltage deviation (large sags), whereas a more aggregated modeling approach in areas of low deviation (small sags) suffices.

Intuitively, this process of estimating voltages must be computationally efficient, otherwise it would destroy the point of employing adaptive distribution system dynamic modeling to improve simulation efficiency (or reduce simulation time). To address this, short-circuit analysis is utilized to quickly estimate the voltage sag following a fault contingency, and subsequently uses the estimation results to selectively model distribution systems with varying fidelity across the transmission system. Compared to a dynamic simulation, short-circuit analysis is a static, phasor solution, translating loads into equivalent impedances, and generators into equivalent voltage sources. Subsequently, voltages are computed across the system in this simplified impedance network.

While conventional short-circuit analysis does not account for dynamic behaviors of loads and DERs, the voltage profiles obtained by short-circuit analysis usually are reasonably close to the depth of voltage sag seen during a dynamic contingency simulation, as they are based on the same network and both capture the fault currents from generators well. Moreover, the short-circuit based estimation results are usually *conservative* (i.e., voltage sags in dynamic simulation are less severe than those obtained by short-circuit analysis) due to the modeling simplification (e.g. voltage support from exciters and fault current contributions from motor loads and DERs are neglected). This is a beneficial characteristic of a voltage screening tool, as it ensures all load buses critical for detailed modeling are appropriately identified. It's effectiveness has been demonstrated in the authors' previous work [8].

C. Proposed Methodology

The proposed adaptive and automated analysis approach is outlined in Fig. 1. For each fault in the list of contingencies, a new, selectively and uniquely modeled system is constructed. First, an estimation of the voltage sag during the fault is computed through short-circuit analysis. Second, the aggregated load underneath each bus is replaced with its respective load representation; either a distribution feeder, or a composite load model, which are determined based on the results from short-circuit analysis when compared to a pre-determined threshold. Third, the T&D dynamic co-simulation is carried out. Finally, this process is repeated, creating a new, adaptively-modeled T&D system for each fault contingency. Note that composite load and feeder models are determined *prior* to the dynamic simulation step. Therefore, distribution system models will not be switched/changed during each dynamic simulation, but rather in between each consecutive one. It is important to highlight that the whole process is automated without labor-intensive model selection and building, paving the way for real-world, large-scale application. The automation process is also negligible to the total simulation time, as short circuit analysis has the same time complexity as a single network

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solution step, and there typically are thousands of network solution steps in a 20-second dynamic simulation.

For comparison studies, the results of this method are compared to a simulation with all composite load models and a simulation with all distribution feeder models, in terms of accuracy and simulation runtime.

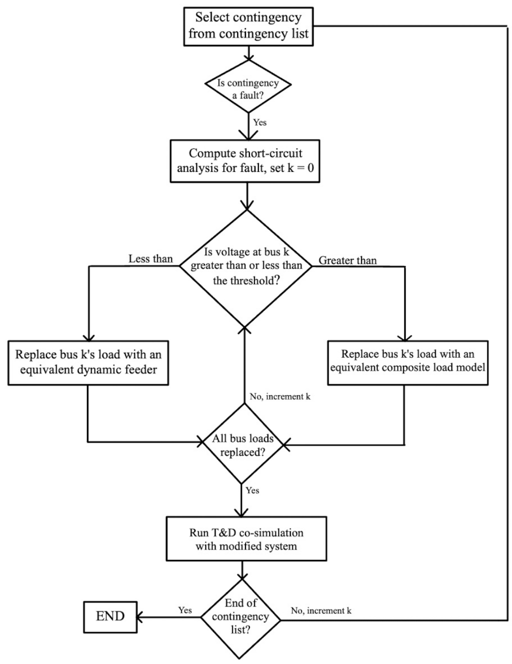

Fig. 1. A flowchart of the proposed adaptive dynamic contingency analysis method

III. Test Cases and Results

A. Test cases

To simulate the effects of individual dynamic loads at different locations of distribution feeders, this study will utilize a feeder depicted in Fig. 2 to represent disaggregated loads. The total load consumption of each feeder is equal to the load that it is replacing, and all load values shown in Fig. 2 are scaled to account for this.

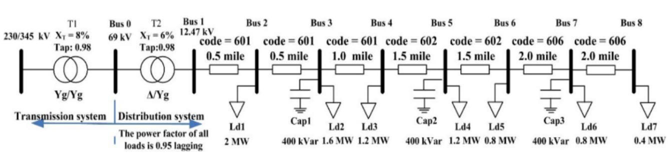

Fig. 2. A feeder for representing distribution systems [6]

The dynamic behaviors of loads on each bus in the distribution feeder can be represented by typical load models including single phase AC motor loads, induction motor loads, and constant ZIP loads. For this study, 30% of each load is modeled as AC single phase motors, 30% is modeled as induction motors, and 40% as constant impedance (in terms of power consumption). These percentages are used in this study as a generalization; it should be noted that selection of these parameters is arbitrary and may not reflect actual composition in some systems, especially across different regions and during varying times of year [9]. Selection of these parameters can and should be adjusted to best model a utility's expected load composition. Higher percentages of dynamic devices will create greater unique effects, particularly fault-induced delayed voltage recovery (FIDVR) for AC motor loads. This study uses the previously mentioned composition for testing purposes of the proposed method, and could be easily extended to cover differing system compositions.

To preserve computational complexity in low-impact regions, this study uses the composite load model (CMPLDW), as proposed by WECC [9]. The composite load model offers aggregated dynamic modeling at one equivalent bus, therefore disregarding the topology of a feeder and heterogeneous composition of loads at different locations in the feeder. For this study, all parameters in the CMPLDW are consistent with the disaggregated feeder's loads for effective comparison.

A key parameter to be chosen is the voltage from short-circuit analysis to use as the threshold between dynamic feeder representation and composite load model representation (low-impact and high-impact regions, respectively). This threshold is highly dependent upon model parameterization, such as motor stalling voltages, load composition, and DER fault ride through specifications. Additionally, this is a threshold that should be conservative as short-circuit analysis will have inherent error within it. Previous work [10] ran detailed sensitivity analysis and determined 0.75 pu measured at the transmission bus level is a reasonable voltage threshold. Above this value, it is expected that voltage drops along a feeder won't excite highly heterogeneous dynamic responses from loads (and DERs), however the same may not be said below this value. For demonstration in this study, a slightly higher value of 0.8 pu is used as the threshold to ensure voltage-sensitive dynamic behavior can be adequately captured.

The IEEE 39-bus and IEEE 300-bus systems are utilized to test the proposed method. A three-phase bus fault is applied at 0.5 seconds for a duration of 0.07 seconds, and the voltage responses are shown over a 20 second simulation. Three separate simulations are conducted for comparison, one with all loads modeled with detailed distribution feeders (denoted as "Full T&D"), one with loads represented by composite load models (denoted as "All CMPLDW Loads"), and another using the proposed adaptive modeling approach (denoted as "Proposed Method"). In all test cases, nearly all loads are replaced with their respective dynamic load model. The voltage response from a bus inside the high-impact zone and another bus near the boundary but outside the high-impact zone are examined to understand the effectiveness of capturing dynamic behavior in the proposed selective modeling approach.

B. Results of IEEE 39-bus system

The first scenario under study considers a fault located at Bus 38 in the IEEE 39-bus system. A depiction of the short-circuit analysis results due to the fault is shown in Fig. 3. Utilizing the proposed method, 9 transmission level loads are

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represented with composite load models, and 7 are represented with full distribution feeders to encapsulate the anticipated dynamic characteristics of the high-impact region. The voltage magnitudes of bus 28 (in the high-impact region) and bus 2 (outside the impact region) over the course of 20 seconds are shown in Fig. 4, along with a zoomed-in plot during and immediately after the fault in Fig 5.

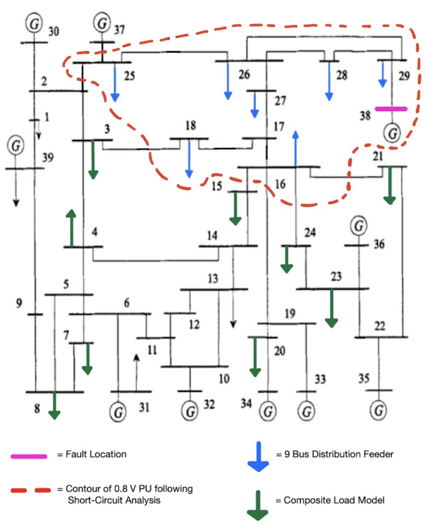

Fig. 3. Example visual of the impact zones found through short-circuit analysis when studying a fault on Bus 38

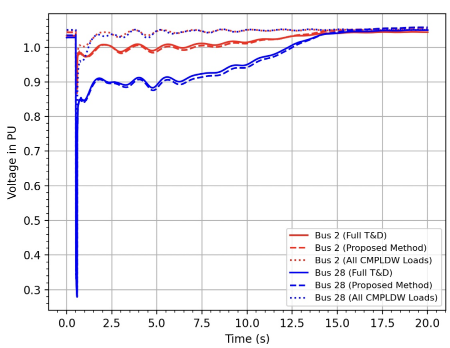

Fig. 4. Voltages at buses 28 and 2 over the whole 20 second simulation

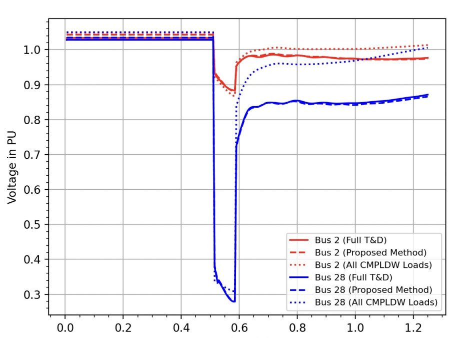

Fig. 5. Voltages at buses 28 and 2 over a short period during and after the fault

Note that the FIDVR issue is adequately captured by the full T&D co-simulation and the proposed method in Fig. 4, but is not seen when all loads are modeled with the composite load model. Additionally, the proposed method captures the transient behavior immediately following the fault, whereas modeling with only composite load models deviates from the full T&D simulation during this period. Furthermore, the simulation run time is significantly reduced with the proposed simulation method, displayed in Table 1. When compared to the full T&D simulation, the proposed method reduces the simulation time in this scenario by a factor of 3.5, while maintaining 99.4% accuracy (the full T&D system is considered to be 100% accurate). On the other hand, the composite load model only simulation exhibits 91.9% accuracy.

C. Results of IEEE 300-bus system

To demonstrate the possible computational complexity savings in a larger power system, another contingency is studied in the IEEE 300 bus system. Results are obtained for a three-phase fault located at Bus 54. A visual of the selectively detailed system when utilizing the proposed method is shown in Fig. 6. Through the selective feeder modeling, 30 transmission level loads are represented with a composite load model, and 10 are represented as disaggregated feeders (these are within the high-impact region). The voltage magnitudes of bus 45 (within the high-impact region) and bus 49 (outside the high-impact region) are shown in Figs. 7 and 8, where Fig. 8 is a zoomed-in plot during a short period immediately after the fault.

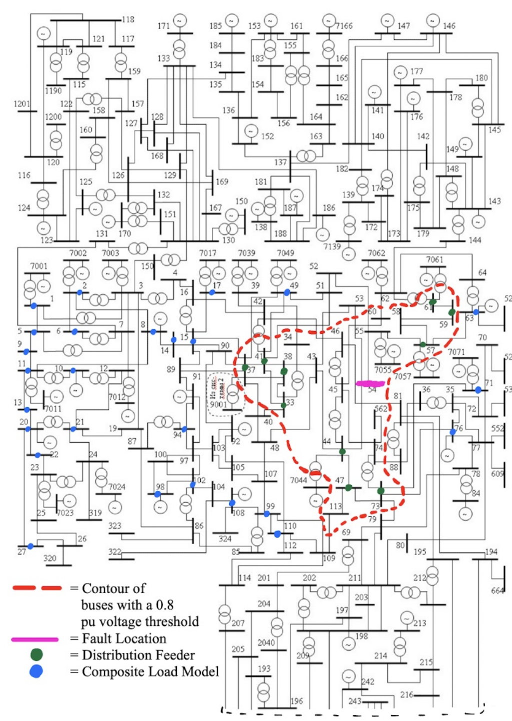

Fig. 6. Example visual of the impact zones found through short-circuit analysis when studying a fault on Bus 54

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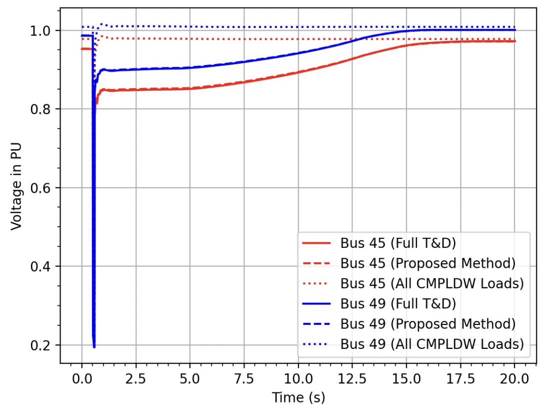

Fig. 7. Voltages at buses 45 and 49 over the 20-second simulation

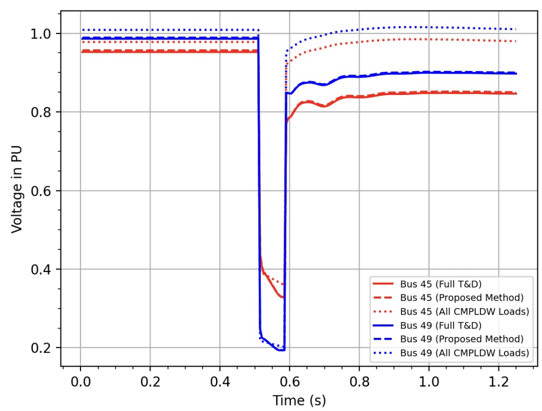

Fig. 8. Voltages at buses 45 and 49 during and immediately after the fault

As depicted in Figs. 7 and 8, the same delayed voltage recovery is not captured in the simulation with all composite load models, however it is adequately captured by the proposed simulation method. Additionally, the simulation runtime was reduced by almost a factor of 6, while maintaining 99.7% accuracy compared to the full T&D simulation. Note that the runtime is decreased by a larger margin in the larger 300-bus test case compared to the 39-bus test case. Due to the ratio of low detailed loads to high detailed loads growing in larger systems (there will be more loads far away from a fault in larger systems, and therefore more loads with retained voltage levels), this trend is expected to continue and increase in ultra-large T&D systems, leading to better speed up.

TABLE I
COMPARISON OF ACCURACY AND SIMULATION RUN TIME REDUCTION

Test System	Metric	Simulation Method		
		Full T&D	**CMPLDW Loads**	**Proposed Method**
IEEE 39 Bus	Accuracy (%)	100%	91.9%	**99.4%**
	Runtime (s)	19.3	1.3	**5.7**
IEEE 300 Bus	Accuracy (%)	100%	91.7%	**99.7%**
	Runtime (s)	86.2	6.4	**14.4**

IV. Conclusion and Future Work

With the recent growth of highly dynamic and nonlinear loads in distribution systems, their effects at the transmission level must be captured. However, the current practice of aggregating distribution systems will be increasingly ineffective at capturing this unique behavior. Meanwhile, modeling distribution feeders in a detailed, disaggregated manner causes substantial increase in computational complexity, which isn't feasible in many applications. To combat this issue, this study effectively demonstrates the use of adaptive distribution system dynamic modeling for transmission-oriented dynamic contingency analysis supported by T&D dynamic co-simulation. The proposed method retains crucial dynamic behaviors in high impact regions, while significantly reducing simulation runtime. Results show that by utilizing short-circuit analysis to estimate voltages following a fault, one can adaptively adjust distribution system model fidelity across the transmission system, creating an efficient yet accurate model. The multi-fidelity system construction is automated, without labor-intensive model selection and building, paving the way for real-world large-scale application.

A crucial topic of future research is systems dominated by DERs. For example, the FIDVR trait seen in this study will trigger their unique volt/var controls. Additionally, some may trip due to the prolonged suppressed voltage. Both of these dynamic effects are closely coupled to the PCC voltage, which may different at varying locations on a feeder. This study opens the door for studies with high penetrations of DERs, by demonstrating the proposed adaptive distribution modeling method as a proof of concept.

References

[1] D. Ramasubramanian, "Analyzing impact of DER on FIDVR - comparison of EMT simulation of a combined transmission and distribution grid with aggregated positive sequence models" EPSR, 2021
[2] A. R. Ramapuram Matavalam, R. Venkatraman and V. Ajjarapu, "Accurate Representation of Distribution System Dynamics in Bulk System Studies by Clusters of Composite Load Models," 2023 IEEE Industry Applications Society Annual Meeting (IAS), Nashville, TN, USA, 2023, pp. 1-5
[3] DER Task Force, "NERC Report on Distributed Energy Resources Task Force Report", February 2017
[4] FERC Staff Report, "Distributed Energy Resources- Technical Considerations for the Bulk Power System", Docket No. AD18-10-000 , February 2018
[5] B. Stott, "Power system dynamic response calculations," in Proceedings of the IEEE, vol. 67, no. 2, pp. 219-241, Feb. 1979
[6] Q. Huang and V. Vittal, "Integrated Transmission and Distribution System Power Flow and Dynamic Simulation Using Mixed Three-Sequence/Three-Phase Modeling," in IEEE Transactions on Power Systems, vol. 32, no. 5, pp. 3704-3714, Sept. 2017
[7] "IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric. Power Systems Interfaces," in IEEE Std 1547-2018 (Revision of IEEE Std 1547-2003), vol., no., pp.1-138, 6 April 2018
[8] O. Cornmesser and Q. Huang, "Identification of Impact Regions for Adaptive Distribution System Modeling in Transmission-Level Dynamic Contingency Analysis," CIGRE Grid of the Future Symposium, Nov. 2024
[9] "Technical Reference on the Composite Load Model," EPRI, Sept. 2020
[10] Q. Huang and V. Vittal, "Application of Electromagnetic Transient-Transient Stability Hybrid Simulation to FIDVR Study," in IEEE Transactions on Power Systems, vol. 31, no. 4, pp. 2634-2646, July 2016

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