

Model Development of Diesel Generator using Volts/Hertz Limiter and Comparing Governor Models for Remote Islanded Microgrids

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Abstract—Diesel generators are an integral component of remote islanded microgrids in rural Alaska. As inverter-based generation is integrated in these microgrids, adequate transient modeling will be necessary as dynamic and transient stability issues can arise with significant contributions of inverter-based generation. A complete transient model of a diesel generator includes models of the machine, exciter, governor, and any relays or other limiting components. Few studies compare the adequacy of various types of diesel generator governor or exciter models or include a volts/hertz (V/Hz) limiting functionality commonly found in diesel generators deployed in such remote islanded microgrids. This paper introduces and compares diesel generator models in response to two load steps against responses from the ACEP PSI lab 400 kVA diesel generator which represents a realistic diesel generator found in remote islanded Alaskan microgrids. A simplified governor model is introduced and compared to the traditional DEGOV governor model, and the functionality of a V/Hz limiter added to a DC4B exciter is demonstrated.

Index Terms—Diesel generators, model parameterization, microgrid, sensitivity analysis.

I. INTRODUCTION

Alaska's remote islanded microgrids are primarily powered by diesel generators, with increasing contributions from inverter-based wind generators in the coastal villages of the state. There is significant interest in adopting more renewable energy with the primary motivation of displacing imported fossil fuels to reduce the cost of electricity and heat [1]. Historically, dynamic or transient modeling of diesel-only microgrids was unnecessary. This was due to there being only one main source of synchronous power generation, whose dynamics were generally well understood and predictable. However, adequate transient modeling of these isolated microgrids is necessary when inverter-based generation or storage is added, as dynamic and transient stability issues can arise with significant contributions of inverter-based generation.

Examples of specific stability issues relevant to remote islanded microgrids which become present with significant

contributions of inverter-based generation include: a high rate of change of frequency due to low inertia [2]–[4], limited fault current contribution impacting protection coordination [4]–[6], harmonic instability due to converter inner control loops [7], [8], interactions between multiple grid-connected converters [7], [9], [10], and lower frequency oscillations introduced by the phase-locked loop (PLL), particularly in weak grids with short circuit ratios less than two [7], [11]. An excellent review of general converter-based generation stability issues is provided in [4], [7], [8], [12]. Therefore, as an integral part of the system, high fidelity transient diesel generator models will need to be created as remote islanded microgrids integrate inverter-based generation.

A complete transient model of a diesel generator includes models of the machine, exciter, governor, and any relays or other limiting components. The machine of a diesel generator is commonly modeled using standard synchronous machine models [13], often simulated in MATLAB[®] Simulink[®] with a six order state-space model, accounting for the stator, field, and damper winding dynamics [14]. Numerous studies have used this model for transient studies, including diesel generators, and have reported their model parameter values [15]–[22]. These model parameter values can be used as a baseline and tuning range to populate new models, as was done in this paper. Additionally, numerous dynamic simulations of diesel generators have implemented simplified diesel genset models, often containing only one or two first order transfer functions to simulate the full diesel generator system [23], [24]. These simplified models will neglect significant dynamics, such as stator, field, damper winding, saturation, and engine delay present in diesel generators. These dynamics can not be ignored as inverter-based generators are operated in tandem with diesel generators, as the controllers of the inverter-based generation function on similar or faster time scales than the diesel generator dynamics, potentially causing interactions.

Common exciter models used in diesel generator transient studies include AC5A [25], [26] and DC4B [27]. The DC4B model has also been identified in the diesel generator exciter documentation at the Alaska Center for Energy and Power's (ACEP) Power System Integration (PSI) laboratory. Addi-

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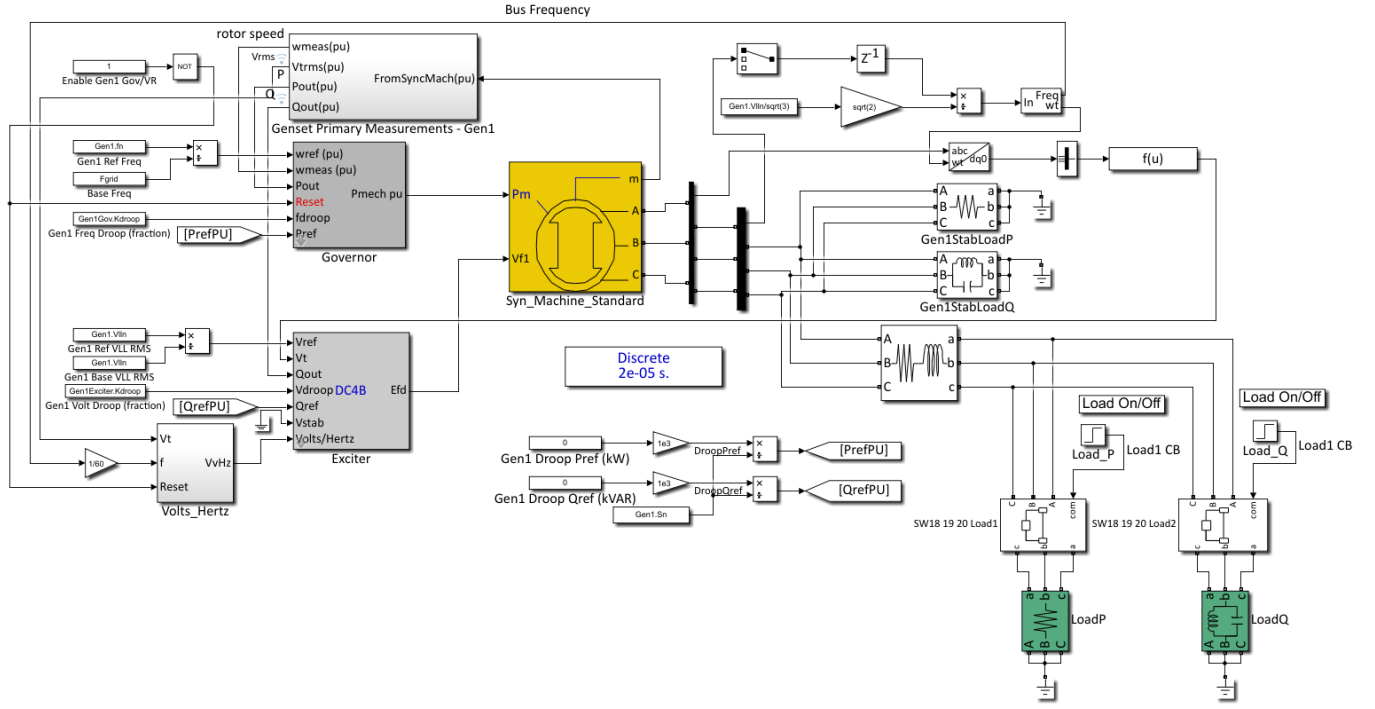


Fig. 1: Simulink[®] model of diesel generator connected to load bank via 480V AC bus.

tionally, to the best knowledge of the authors, none of the implementations of exciter models for diesel generators in the literature include volt/hertz (V/Hz) limiting functionality. A V/Hz limiter is commonly seen in other primary generation units [28]–[30], has been identified in the ACEP PSI laboratory diesel exciter documentation, and represents diesel electric generators implemented in remote islanded microgrids of Alaska.

Diesel governors have been modeled in the literature with a wide range of implementations from the simple single time constant models [23], [24], to the DEGOV model [31] which contains six time constants and engine delay. Parameterization of governor models can be challenging to perform due to parameter inter-dependency and interchangeability, such as in the DEGOV governor model with numerous interchangeable time constants.

There are few studies where these diesel generator models have been benchmarked against diesel generator field or lab data. The microgrid model of Igiugig, Alaska which contains an 80 kVA diesel generator and ten 2 kW Type-4 wind generators was validated against a symmetrical three-phase fault [17]. Other studies including experimental or field results had diesel generators that were much smaller (16 kVA) [32] or much larger (3.125–3.5 MVA) [16], [33] than what is found in a remote islanded microgrid setting in Alaska [1].

This paper introduces and compares diesel generator models in response to two load steps against responses from the ACEP PSI lab 400 kVA diesel generator which represents a realistic diesel generator found in remote islanded Alaskan microgrids. This work introduces a simplified governor model

and compares it to the traditional DEGOV governor model. This paper also implements a V/Hz limiter within a DC4B excitation model. All simulation results are compared against laboratory data collected at the ACEP PSI laboratory.

The contributions of this paper are 1) introduction of a simplified governor model with comparison to the DEGOV governor model against measured laboratory test data from a 400 kVA diesel generator and 2) demonstration of a V/Hz limiter in the exciter model for islanded microgrid operation of a diesel generator.

The remainder of this paper is organized as follows. Section II outlines the modeling of system components of the diesel generator. Section III describes the parameter identification of the diesel generator and sensitivity analysis. In Section IV the simulation results of the diesel generator model for two load steps are reviewed and validated against the test results. In conclusion, Section V discusses the implication of the results found in this study.

II. SIMULATION MODEL

A MATLAB[®] Simulink[®] model of the laboratory setup, outlined in Section III-A, was created and is shown in Fig. 1. The diesel generator model consists of three components: the synchronous machine, the exciter, and the governor which are outlined in the following subsections and the variables are defined in Table I.

A. Machine Model

The machine model used in this paper is the standard synchronous generator model for a 406 kVA machine modeled in the dq reference frame and available in Simulink[®] [14].

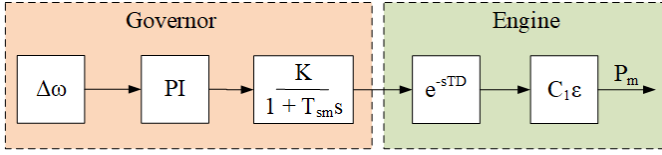


Fig. 4: Simple governor block diagram for diesel generator operation in isochronous mode [37].

T_1, T_2, T_3, T_4, T_5 , and T_6 are the actuator time constants. T_D is the engine delay.

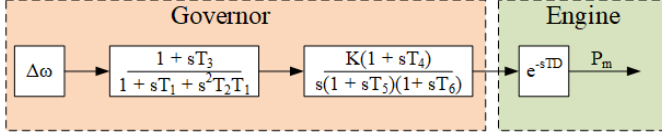


Fig. 5: Woodward diesel governor DEGOV block diagram [39].

III. SIMULATION RESULTS

The model developed for the diesel generator in this work is simulated for two different load steps i.e. 1) Large step-up: 80 kW and 0 kVar to 240 kW and 160 kVar and 2) Large step-down: 240 kW and 160 kVar to 80 kW. The model parameters were selected to obtain the best results over different load step changes in comparison to the laboratory results without significant deviation from the nominal values acquired from the literature and the CAT C15 diesel generator datasheet and their values are presented in Table I.

A. Experimental Setup and Data Collection

ACEP's PSI laboratory has a full-scale microgrid testbed designed to represent typical Alaskan remote islanded microgrids at medium voltage levels. The PSI laboratory components used in this study include the CAT C15 400 kVA diesel generator and the two 313 kVA loadtec resistive/inductive load banks connected via a 480 V AC bus. Data was collected using a Yokogawa DL850 oscilloscope with a 50 kHz sampling rate. All three phases of instantaneous voltage (V_{an}, V_{bn}, V_{cn}) and line currents (I_a, I_b, I_c) were collected. The root mean square (RMS) voltage, current, frequency, and real and reactive power were calculated using the measured instantaneous voltage and currents signals.

B. Simple Governor and DEGOV Governor Model Comparisons

The active and reactive power, voltage, and frequency responses of the diesel generator models with the simple governor and the DEGOV governor in comparison to the laboratory data are shown in Fig. 6 for the two load step changes.

The laboratory results demonstrate that the recovery time of the diesel generator from the initial load step is approximately within 1 second. However, the frequency response has more

TABLE II: The nRMSE response error between simulation results and the 400 kVA diesel generator responses.

Load Step	Response Type	nRMSE Error (%)	
		Simple Governor	DEGOV
Large Load Step Up: 80 kW and 0 kVar to 240 kW and 160 kVar	Active Power (P)	5.81	5.15
	Reactive Power (Q)	5.27	4.92
	Voltage (v)	6.24	6.01
	Frequency (f)	13.88	12.41
Large Load Step Down: 240 kW and 160 kVar to 80 kW and 0 kVar	Active Power (P)	6.42	6.67
	Reactive Power (Q)	6.09	6.16
	Voltage (v)	6.73	7.00
	Frequency (f)	11.43	15.39

delayed and variable recovery. Significant transients are seen in the frequency response after the initial swing at the time of the load step. Additionally, the ringing after recovery to 60 Hz in the lab data shows that the gain of the governor is approaching the high limit. Numerous factors impact these secondary transient responses, such as non-linear engine delays. Restrictions in both air flow and fuel flow can also add to the recovery time it takes an engine to return to the rated speed and frequency irrespective of the controller action, such as the governor. Inconsistencies between the simple governor and DEGOV responses and the laboratory data seen in Fig. 6 exist, this is most predominately in the frequency response. In particular, this is most prevalent with the transient response of the load step up where there is a sharp dip at 0.2 s prior to the full initial transient swing at around 0.4 s in the frequency response, and secondary transients occurring from 0.5 s to 1.6 s. Multi-sourced engine delays could impart the secondary transients seen in the frequency response, or they could be due to differences in actuator design compared to actuator transfer functions found in the governor models. Data-driven models will be pursued in future work to identify potentially more suitable actuator and engine delay functions.

The nRMSE error between the response of the diesel generator model with the simple governor and DEGOV governor model and the measured data from the lab test for both load steps is shown in Table II. We can observe from Table II and Fig. 6 that the error in the response of the diesel generator simulation model using both governor models is almost similar. However, the error in the frequency response is greater for both governor models in comparison to the other responses. Between the two governor models presented in this work, the simple governor model utilizes a PID controller, and there are well established methods like the Ziegler-Nichols method to tune PID controllers. Hence the proposed simple governor model would be a more approachable alternative to the DEGOV model for future applications and the simple governor exhibits similar responses to the DEGOV model.

C. Volts/Hertz Limiter Functionality

The V/Hz limiting function is a control feature within the automatic voltage regulator (AVR) as shown in Fig. 2 that limits the exciter set point voltage to mitigate over-fluxing in over-voltage or under-frequency conditions. The reference of

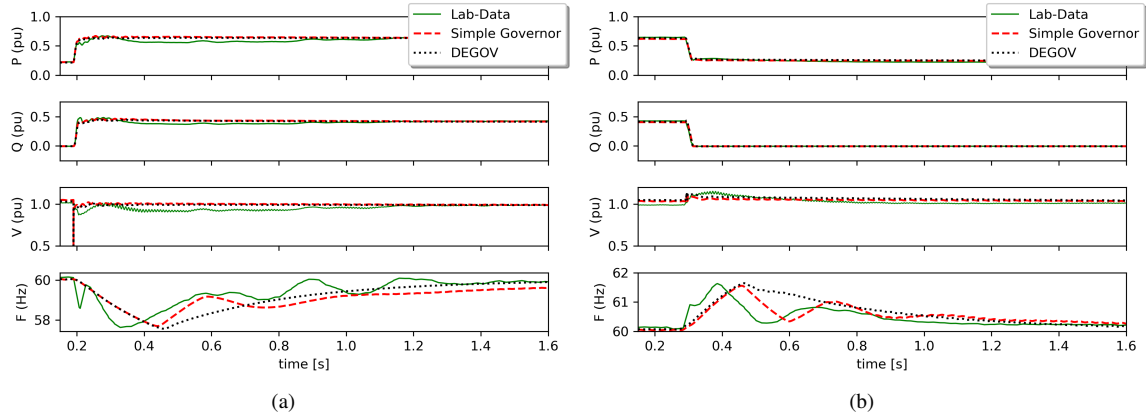


Fig. 6: Diesel generator response with simple governor and DEGOV model for the load step change (a) 80 kW and 0 kVar to 240 kW and 160 kVar, (b) 240 kW and 160 kVar to 80 kW and 0 kVar.

the V/Hz limiter is set to 1.04 pu and is tabulated from the data provided in CAT C-15 diesel generator datasheet. After the load step change from 80 kW and 0 kVAR to 240 kW and 160 kVAR, the V/Hz limiter provides a corrective action at 1.04 pu reducing the generator voltage by 2.5% as compared to the corrective action without the limiter as shown in Fig. 7. We can also observe from Fig. 7 that the corrective action for frequency response with V/Hz limiter is almost 0.05 s faster. Similar responses were obtained for other load step change. The parameter values for the V/Hz limiter implemented in this work are shown in Table III.

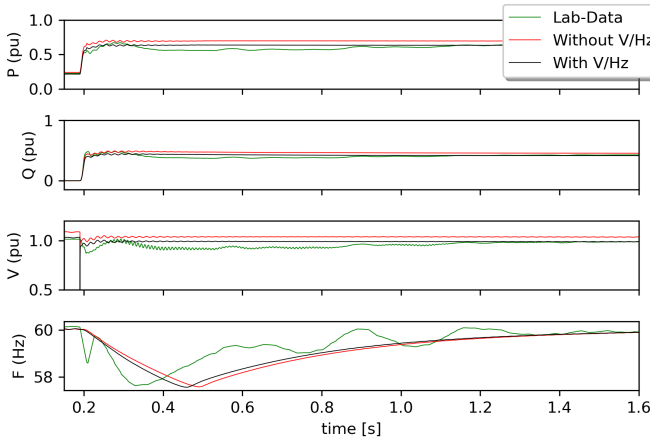


Fig. 7: Comparison between the diesel generator response with and without the V/Hz limiter for load step change of 80 kW and 0 kVAR to 240 kW and 160 kVAR.

IV. CONCLUSION

The mathematical model of the V/Hz limiter excitation system and the comparison between two governor models of the diesel generator are presented in this work. The V/Hz limiter implementation is demonstrated and provides corrective action for the terminal voltage, with a V/Hz setpoint of 1.04

TABLE III: Parameter values for V/Hz limiter

V/Hz Parameters	Tabulated	Minimum	Maximum
K_1	1000	500	2000
K_{max}	1	0.95	1.05
K_{min}	0	0	0
K_2	0.007	0.001	0.1
V/Hz setpoint (pu)	1.04	1.01	1.05

pu, which limits the voltage and reactive power during the exhibited load step changes. The V/Hz implementation also provides faster corrective action on the frequency response. Also, the output response of the developed diesel generator model is compared with the laboratory measurements of the 400 kVA CAT C15 diesel generator at the ACEP PSI lab for four different load step changes. By comparing the output response of the diesel generator model with the measurement data, we can conclude that both the simple governor and DEGOV model capture the transient dynamics equally well, but the simple governor model is easier to tune and implement. Hence, a diesel generator model with a simple governor would be a more approachable alternative for future applications. However, there is an opportunity for improved governor actuator and engine delay models to better capture secondary frequency transient responses and this will be presented in the future work.

REFERENCES

- [1] G. P. Holdmann, R. W. Wies, and J. B. Vandermeer, "Renewable Energy Integration in Alaska's Remote Islanded Microgrids: Economic Drivers, Technical Strategies, Technological Niche Development, and Policy Implications," *Proceedings of the IEEE*, vol. 107, no. 9, pp. 1820–1837, 2019.
- [2] U. Markovic, O. Stanojev, E. Vrettos, P. Aristidou, and G. Hug, "Understanding stability of low-inertia systems," *engrXiv preprint*, 2019.
- [3] U. Tamrakar, D. Shrestha, M. Maharjan, B. P. Bhattarai, T. M. Hansen, and R. Tonkoski, "Virtual inertia: Current trends and future directions," *Applied Sciences*, vol. 7, no. 7, 2017. [Online]. Available: <https://www.mdpi.com/2076-3417/7/7/654>
- [4] H. Holtinen, J. Kiviluoma, D. Flynn, C. Smith, A. Orths, P. B. Eriksen, N. A. Cutululis, L. Soder, M. Korpas, A. Estanqueiro, J. Macdowell, A. Tuohy, T. K. Vrana, and M. O'Malley, "System impact studies

- for near 100% renewable energy systems dominated by inverter based variable generation,” *IEEE Transactions on Power Systems*, pp. 1–1, 2020.
- [5] B. Kroposki, C. Pink, R. DeBlasio, H. Thomas, M. Simões, and P. K. Sen, “Benefits of power electronic interfaces for distributed energy systems,” *IEEE Transactions on Energy Conversion*, vol. 25, no. 3, pp. 901–908, 2010.
 - [6] E. Muljadi, N. Samaan, V. Gevorgian, J. Li, and S. Pasupulati, “Different factors affecting short circuit behavior of a wind power plant,” in *2010 IEEE Industry Applications Society Annual Meeting*, 2010, pp. 1–9.
 - [7] Power System Dynamic Performance Committee, “Stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic interfaced technologies,” Tech. Rep., April 2020. [Online]. Available: https://resourcecenter.ieee-pes.org/publications/technical-reports/PES_TP_TR77_PSDP_stability_051320.html
 - [8] M. Farrokhhabadi *et al.*, “Microgrid stability definitions, analysis, and examples,” *IEEE Transactions on Power Systems*, vol. 35, no. 1, pp. 13–29, 2020.
 - [9] C. Yoon, H. Bai, R. N. Beres, X. Wang, C. L. Bak, and F. Blaabjerg, “Harmonic stability assessment for multiparalleled, grid-connected inverters,” *IEEE Transactions on Sustainable Energy*, vol. 7, no. 4, pp. 1388–1397, 2016.
 - [10] E. Ebrahimzadeh, F. Blaabjerg, X. Wang, and C. L. Bak, “Modeling and identification of harmonic instability problems in wind farms,” in *2016 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2016, pp. 1–6.
 - [11] D. Wu, G. Li, M. Javadi, A. M. Malyscheff, M. Hong, and J. N. Jiang, “Assessing impact of renewable energy integration on system strength using site-dependent short circuit ratio,” *IEEE Transactions on Sustainable Energy*, vol. 9, no. 3, pp. 1072–1080, 2018.
 - [12] G. San, W. Zhang, X. Guo, C. Hua, H. Xin, and F. Blaabjerg, “Large-disturbance stability for power-converter-dominated microgrid: A review,” *Renewable and Sustainable Energy Reviews*, vol. 127, p. 109859, 2020. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S1364032120301532>
 - [13] P. Kundur, *Power System Stability and Control*, 1994.
 - [14] Mathworks, “Synchronous Machine,” <https://www.mathworks.com/help/phymod/sps/powersys/ref/synchronousmachine.html>, 2020.
 - [15] H. Nikkhajoei and R. H. Lasseter, “Distributed generation interface to the CERTS microgrid,” *IEEE Transactions on Power Delivery*, vol. 24, no. 3, pp. 1598–1608, 2009.
 - [16] K. Yeager and J. Willis, “Modeling of emergency diesel generators in an 800 megawatt nuclear power plant,” *IEEE Transactions on Energy Conversion*, vol. 8, no. 3, pp. 433–441, 1993.
 - [17] A. AbuHussein, N. Ingalls, M. A. H. Sadi, and M. AbuAgreb, “Transient stability microgrid model for arctic community integration,” in *2020 IEEE/PES Transmission and Distribution Conference and Exposition (T D)*, 2020, pp. 1–5.
 - [18] O. Sakamoto, “An example of a diesel generator model with fluctuating engine torque for transient analysis using xtap,” *Journal of International Council on Electrical Engineering*, vol. 6, no. 1, pp. 31–35, 2016. [Online]. Available: <https://doi.org/10.1080/22348972.2016.1139775>
 - [19] W. B. Gish, “Small induction generator and synchronous generator constants for dsg isolation studies,” *IEEE Transactions on Power Delivery*, vol. 1, no. 2, pp. 231–239, 1986.
 - [20] M. Mirosevic, Z. Maljkovic, and D. Pavlinović, “The dynamics of diesel-generator unit in isolated electrical network,” *International Journal of Renewable Energy Research*, vol. 1, pp. 126–133, 2011.
 - [21] S. Eberlein, A. Heider, and K. Rudion, “Modelling and control optimization of diesel synchronous generators in lv microgrids,” in *2018 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, 2018, pp. 1–6.
 - [22] P. P. Leza, “Transient Study in Diesel Synchronous Generator,” Ph.D. dissertation, Universidad De Oviedo, 2017.
 - [23] S. A. Papathanassiou and M. P. Papadopoulos, “Dynamic characteristics of autonomous wind–diesel systems,” *Renewable Energy*, vol. 23, no. 2, pp. 293–311, 2001. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0960148100001804>
 - [24] M. Datta, T. Senjyu, A. Yona, T. Funabashi, and C.-H. Kim, “A frequency-control approach by photovoltaic generator in a pv–diesel hybrid power system,” *IEEE Transactions on Energy Conversion*, vol. 26, no. 2, pp. 559–571, 2011.
 - [25] T. Theubou, R. Wamkeue, and I. Kamwa, “Dynamic model of diesel generator set for hybrid wind-diesel small grids applications,” in *2012 25th IEEE Canadian Conference on Electrical and Computer Engineering (CCECE)*, 2012, pp. 1–4.
 - [26] N. T. Janssen, R. A. Peterson, and R. W. Wies, “Development of a Full-Scale-Lab-Validated Dynamic Simulink® Model for a Stand-Alone Wind-Powered Microgrid,” ser. ASME Power Conference, vol. 2, 07 2014, v002T09A004. [Online]. Available: <https://doi.org/10.1115/POWER2014-32035>
 - [27] B. Idlbi, “Dynamic Simulation of a PV-Diesel-Battery Hybrid Plant for Off Grid Electricity Supply,” Ph.D. dissertation, The University of Kassel, 2012.
 - [28] A. B. Piardi, J. R. Pesente, R. B. Otto, and R. A. Ramos, “Evaluation of volts/hertz and over-excitation limiters acting under unbalanced load conditions,” in *2013 IEEE Power Energy Society General Meeting*, 2013, pp. 1–5.
 - [29] D. K. Maina, M. J. Sanjari, and N.-K. C. Nair, “Voltage and frequency response of small hydro power plant in grid connected and islanded mode,” in *2018 Australasian Universities Power Engineering Conference (AUPEC)*, 2018, pp. 1–7.
 - [30] I. T. F. on Excitation Limiters, “Recommended models for overexcitation limiting devices,” *IEEE Transactions on Energy Conversion*, vol. 10, no. 4, pp. 706–713, 1995.
 - [31] PowerWorld Corporation, “Governor DEGOV,” https://www.powerworld.com/WebHelp/Content/TransientModels_HTML/Governor%20DEGOV.htm, 2020.
 - [32] Q. Long, H. Yu, F. Xie, N. Lu, and D. Lubkeman, “Diesel Generator Model Parameterization for Microgrid Simulation Using Hybrid Box-Constrained Levenberg-Marquardt Algorithm,” *IEEE Transactions on Smart Grid*, vol. 12, no. 2, pp. 943–952, 2021.
 - [33] I. Hassan, R. Weronick, R. Bucci, and W. Busch, “Evaluating transient performance of standby diesel-generator units by simulation,” *IEEE Transactions on Energy Conversion*, vol. 7, no. 3, pp. 470–477, 1992.
 - [34] PowerWorld Corporation, “Exciter DC4B and ESDC4B,” https://www.powerworld.com/WebHelp/Content/TransientModels_HTML/Exciter%20DC4B%20and%20ESDC4B.htm, 2020.
 - [35] L. Che and M. Shahidehpour, “Adaptive Formation of Microgrids With Mobile Emergency Resources for Critical Service Restoration in Extreme Conditions,” *IEEE Transactions on Power Systems*, vol. 34, no. 1, pp. 742–753, 2019.
 - [36] D. Nikolic, M. Negnevitsky, and M. de Groot, “Effect of the Diesel Engine Delay on Stability of Isolated Power Systems with High Levels of Renewable Energy Penetration,” in *2015 International Symposium on Smart Electric Distribution Systems and Technologies (EDST)*, 2015, pp. 70–73.
 - [37] A. M. O. Haruni, A. Gargoom, M. E. Haque, and M. Negnevitsky, “Dynamic operation and control of a hybrid wind-diesel stand alone power systems,” in *2010 Twenty-Fifth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2010, pp. 162–169.
 - [38] “Woodward Diesel Governor Model,” https://www.powerworld.com/WebHelp/Content/TransientModels_HTML/Governor%20DEGOV.htm.
 - [39] NEPLAN, “Turbine-governor models: Standard dynamic turbine-governor systems in neplan power system analysis too.” [Online]. Available: https://www.neplan.ch/wp-content/uploads/2015/08/Nep_TURBINES_GOV.pdf