

Improved Generator Voltage Control in Power Flow Solutions

Brandon M. Allison and Thomas J. Overbye

Department of Electrical Engineering
Texas A&M University
College Station, TX
brandona@tamu.edu, overbye@tamu.edu

James D. Weber

PowerWorld Corporation
Champaign, IL
weber@powerworld.com

Abstract – Generator voltage control in power flow solutions may be better represented by a general $Q(V)$ function instead of the current standard PV/PQ modeling. Voltage control modeling in power flow simulations plays an important role in representing one of the more important aspects of physical power systems. Historically, PV/PQ bus modeling has been used as a standard across simulation packages. However, physical systems provide system generators with a setpoint tolerance, which may not be well represented by the strict rule-based approach in PV/PQ modeling. Instead, the voltage control may be better represented by a “reactive power is a function of voltage” control model, as this better correlates with an actual AVR implementation. Some system characteristics of PV/PQ modeling and two $Q(V)$ function models are presented in the sections that follow.

Index Terms—Generator Setpoint Tolerance, PV, PQ, Bus

I. INTRODUCTION

Solving power flow systems in simulation models has been an area of interest and growth for at least 60 years [11], [15], [19], [23]. During this period, PV/PQ bus modeling [14] has been the standard for mimicking physical AVR voltage control among commercial simulation software packages, as well as in research and academic settings.

A. Traditional PV/PQ Switching Logic

The PV/PQ modeling method labels each bus that has a real power injection (generators [+]) and loads [-]) as either known real power and voltage (PV), or known real power and reactive power (PQ). When using a case that has no previous solution, the bus types are determined by setting all busses to type PV and solving. If a generator has a reactive power violation, its regulated bus is changed to a PQ bus and the power flow is resolved. Other bus type changes are made based on the PV/PQ switching logic shown in Table 1. This process of updating the bus types and resolving is repeated until no bus updates are required and all mismatches are within a small tolerance [23]. The PV/PQ switching logic is as follows:

Table 1: PV/PQ switching logic [23]

Type Change	PV, if BusType = PV and $Q_{\min} < Q < Q_{\max}$	
	PV, if BusType = PQ, $Q = Q_{\max}$, and $V < V_{\text{set}}$	
New Bus Type =	{	PV, if BusType = PQ, $Q = Q_{\min}$, and $V > V_{\text{set}}$
		PQ, if BusType = PQ, $Q = Q_{\max}$, and $V \geq V_{\text{set}}$
		PQ, if busType = PQ, $Q = Q_{\min}$, and $V \leq V_{\text{set}}$
		PQ, if BusType = PV, and $Q < Q_{\min}$, or $Q > Q_{\max}$

In a physical system, generators are equipped with Automatic Voltage Regulators (AVR) that adjust their reactive power output to regulate voltage. This control is based on the generator’s point of interconnect (POI) bus voltage and the generator’s assigned voltage setpoint [17] with an allowable tolerance band (with example values of ± 0.01 pu in [17]). Although each generator may have a different AVR implementation, in general they will operate with reactive power as some inversely related function of voltage. Each generator in the physical system must have an AVR that complies with its interconnect’s regulations.

The Electric Reliability Council of Texas (ERCOT) manages the electric grid covering most of the US state of Texas and is responsible for maintaining its reliability. In the ERCOT interconnect, generators must maintain voltage within ± 0.02 pu of the voltage setpoint, or provide reactive power at their minimum or maximum capability [8] (depending on the sign of the difference). This response requirement is much more relaxed than the “sharp” function that is implemented with PV/PQ modeling.

Although it may be logical to immediately implement some arbitrary voltage control function which theoretically matches a physical AVR function, some method of metrics is needed. The term “Dynamic Reactive Reserves” refers to “reserving” the ability to rapidly adjust the reactive power injection at any given bus, which may be necessary in a dynamic event. This is typically done by ensuring that rapid response (dynamic) reactive devices always have the capability to adjust their reactive injection in either direction [7]. These dynamic reactive devices can include many types of devices, but the largest contributors to reserves are typically generators. For a generator to effectively provide dynamic reserves, it must not operate at either the minimum or maximum MVAR limit.

As Independent System Operators (ISOs) actively seek to maintain system reliability and Dynamic Reactive Reserves, they will adjust static reactive devices (such as discrete capacitors) and voltage setpoints to minimize the number of generators operating near one of the two reactive power limits [7], [12]. Because of this, physical systems typically do not have many generators which operate at their reactive power limits. By contrast, many steady-state power flow cases, which are employed by various ISOs in planning studies, inaccurately solve with additional generators operating at a reactive limit.

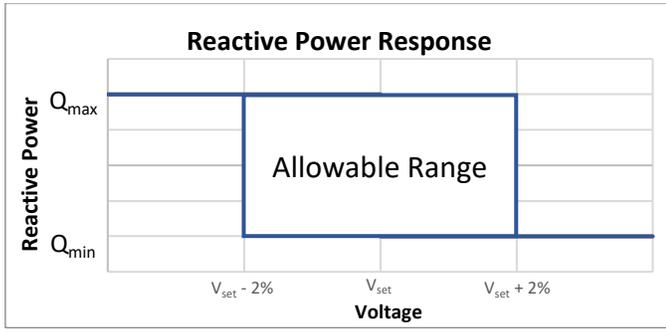


Figure 1. Setpoint Tolerance Allowable Functions

In sections that follow, two new voltage control modeling methods will be presented along with several case studies.

II. METHOD

As noted, in a physical system, each system generator has an obligation to deploy and operate an Automatic Voltage Regulator (AVR) which will adjust the units reactive power output and maintain voltage within regulations. Most interconnects provide a setpoint tolerance, as well as the minimum reactive power absorption and production levels required during boundary voltage events [8], [24]. Using a tolerance of ± 0.02 pu, the allowed reactive power functions include anything that fits in the “box” of Figure 1.

Most power flow steady state simulation packages solve a power flow using an iterative approach, such as Newton’s method [19]. The power flow equations that are typically used in steady state simulation have the form of [14]:

$$P_k = V_k \sum_{n=1}^N V_n [G_{kn} \cos(\delta_k - \delta_n) + B_{kn} \sin(\delta_k - \delta_n)] \quad (1)$$

$$Q_k = V_k \sum_{n=1}^N V_n [G_{kn} \sin(\delta_k - \delta_n) + B_{kn} \cos(\delta_k - \delta_n)] \quad (2)$$

Here, P_k and Q_k are the real and reactive power injections at each bus k . G_{kn} and B_{kn} values for each pair of buses (k and n) are known from the Y bus, which is defined as an input. In order to uniquely define a (stable) solution (which consists of solving for V and δ at each bus), at least two of P_k , Q_k , V_k and δ_k must be defined at each bus k . The PV/PQ modeling method directly defines P_k and V_k , or P_k and Q_k respectively. Another method may to define one unknown directly and define a second in relation to a solvable value (like defining P and $Q(V)$).

The traditional standard of PV/PQ modeling will result in the response shown in Figure 2. PV buses correspond with any bus whose voltage and reactive power fall on the vertical line, and PQ buses correspond with the two ending horizontal lines.

Many other methods of modeling voltage control are possible, provided that they specify real power, along with voltage or reactive power; or some relation between the two (such as $Q(V)$). Here, two functions using a method with reactive power as a function of voltage are presented. These include an inverse linear function, and a piecewise linear.

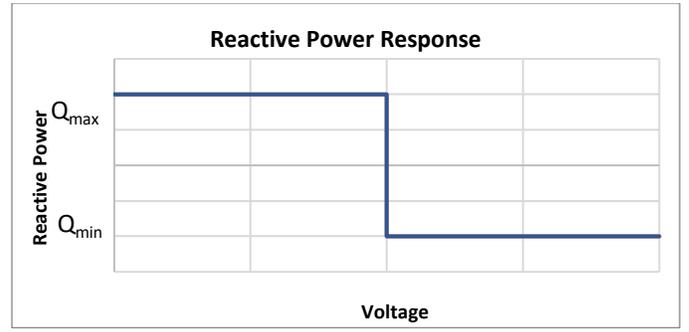


Figure 2. PV/PQ modeling $Q(V)$

deadband function. They are intended to implement a simple linear AVR response as well as an AVR response with a deadband.

The linear function is the result of “drawing a line” diagonally through the Allowable Range in Figure 1, or through the two points:

$$(V_{\min}, Q_{\max}) | (V_{\max}, Q_{\min})$$

where:

$$V_{\min} = V_{\text{set}} - \text{Setpoint Tolerance}$$

$$V_{\max} = V_{\text{set}} + \text{Setpoint Tolerance}$$

And the function becomes:

$$Q(V) = \begin{cases} Q_{\max}, & \text{for } V < V_{\text{set}} - ST. \\ Q_{\min} + (Q_{\max} - Q_{\min}) \frac{V - V_{\min}}{V_{\max} - V_{\min}}, & \text{for } V_{\text{set}} - ST < V < V_{\text{set}} + ST \\ Q_{\min}, & \text{for } V > V_{\text{set}} + ST \end{cases} \quad (3)$$

where:

Q_{\max} is the generator high reactive power limit

Q_{\min} is the generator low reactive power limit

V_{set} is the Voltage Setpoint

ST is the setpoint tolerance

This AVR response of this function is shown in Figure 3. As noted in [17] the Q_{\max} and Q_{\min} values may actually be a function of the generator’s real power output. However, in the algorithm being presented here for reactive power control, the real power and hence these limits, may be considered fixed.

Next a piecewise linear function is considered, which adds a dead-band near the voltage setpoint where there is no reactive

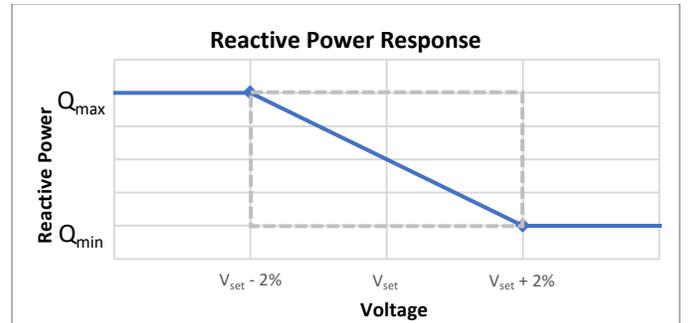


Figure 3. Inverse Linear $Q(V)$

power supplied. With a 0.01 pu dead-band and a 0.02 pu setpoint tolerance, the function is as shown in Figure 4.

$$Q(V) = \begin{cases} \frac{Q_{\max} - (-Q_{\max})}{ST-DB} V - \frac{(V_{\text{set}}-ST)Q_{\max}}{ST-DB} & \text{for } V < V_{\text{set}} - ST \\ 0 & \text{for } V_{\text{set}} - ST < V < V_{\text{set}} - DB \\ \frac{Q_{\min} - (V_{\text{set}}+ST)Q_{\min}}{ST-DB} V - \frac{(V_{\text{set}}+ST)Q_{\min}}{ST-DB} & \text{for } V_{\text{set}} - DB < V < V_{\text{set}} + DB \\ \frac{Q_{\min} - (V_{\text{set}}+ST)Q_{\min}}{ST-DB} V - \frac{(V_{\text{set}}+ST)Q_{\min}}{ST-DB} & \text{for } V_{\text{set}} + DB < V < V_{\text{set}} + ST \\ Q_{\min} & \text{for } V > V_{\text{set}} + ST \end{cases} \quad (4)$$

where:

- Q_{\max} is the generator high reactive power limit
- Q_{\min} is the generator low reactive power limit
- V_{set} is the Voltage Setpoint
- DB is the deadband
- ST is the setpoint tolerance
- $0 < DB < ST, Q_{\max} > 0, Q_{\min} < 0$

This function's reactive power response is significantly relaxed from the PV/PQ function, and it may cause a significant difference in the solution voltage profile. The AVR response of this function is shown in Figure 4. The differences in physical AVR implementations and the typical PV/PQ simulation voltage control modeling likely contribute to the discrepancy seen in the number of generators which operate at reactive power in simulations.

III. CASE STUDY

In this section, the different voltage control modeling methods are explored in detail. Each model's effect on the voltage profile, contingency analysis and dynamic reactive reserves are presented.

For the case study, three synthetic grid cases are used [21]. These grid cases are entirely fictional, but are sufficiently complex and representative of the characteristics of physical actual electric grids to allow for research studies. Three synthetic grids have 200, 2000 and 10,000 buses respectively.

A. 200-bus case

The figures that follow show the voltage profile, contingency analysis, and reactive reserves results from the 200-bus case. The most obvious difference in the three methods comes from the voltage contours. These are shown in Figures 5 through 7. The voltage contour visualization represents the

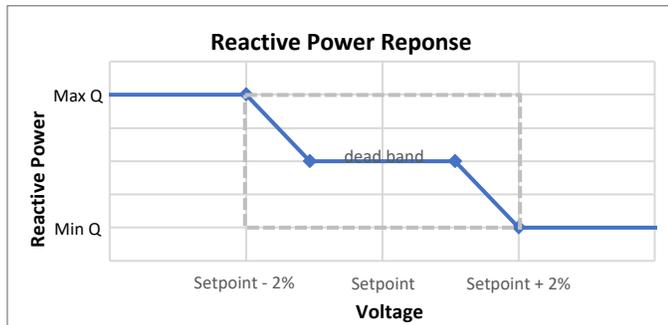


Figure 4. Piecewise Linear Function Q(V)

geographical average voltage distribution over each of the individual buses [13]. Here, blue is used for high voltages, and red for low voltages.

As the cases change from the PV/PQ model, to the linear model, to the piecewise deadband model, system voltages approach more extreme levels. However, there are no base case voltage or branch MVA limit violations in any of the three cases.

Table 2 presents the number of generators in each case which are operating at either one of their reactive power limits. The PV/PQ case has the most limit operating generators. Because physical systems typically maintain significant Dynamic Reactive Reserves, the linear Q(V) function method best represents a physical system in regards to this metric.

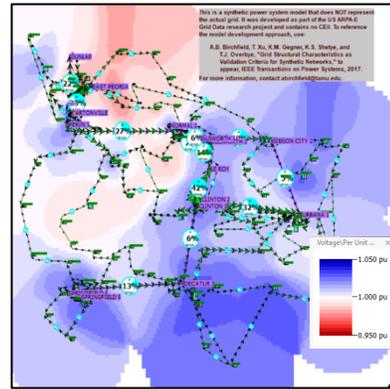


Figure 5, PV/PQ modeling

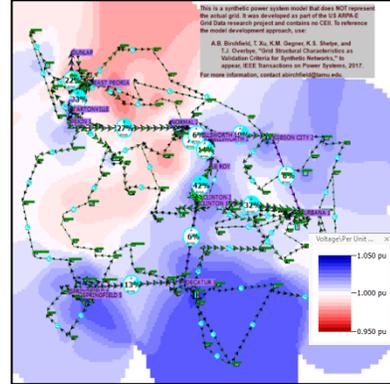


Figure 6, Linear Q(V) Modeling

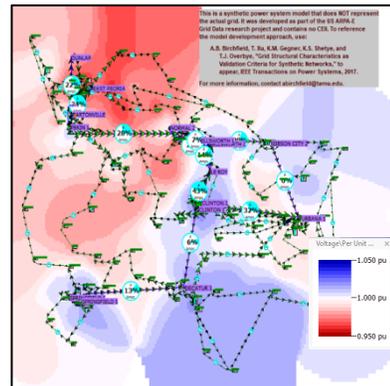


Figure 7, Piecewise Linear Q(V) Modeling

In the contingency analysis, shown in Table 3, the piecewise deadband function had the most violations. These results again show that the different solutions from the three modeling methods may affect system planning decisions.

Table 2: 200 Bus Case Dynamic Reactive Reserves

Number of Generators	Low Q Limit	High Q limit	Total
PV/PQ	13	0	13
Linear Q(V)	2	0	2
Piecewise Q(V)	6	0	6

Table 3: 200 Bus Case Contingency Analysis

Contingency Violations	Max Branch	Low Bus V	High Bus V	Total Violations
PV/PQ	0	2	0	2
Linear Q(V)	0	2	0	2
Piecewise Q(V)	0	5	0	5

200-Bus Case Voltage Profiles

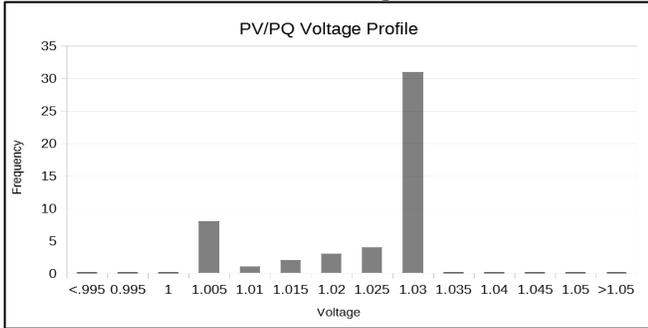


Figure 8: PV/PQ Modeling

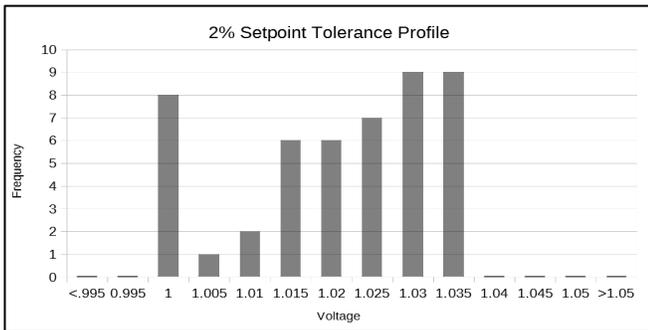


Figure 9: Linear Q(V) Modeling

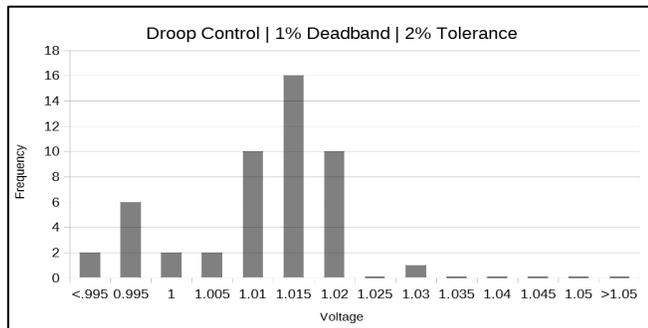


Figure 10: Piecewise Linear Q(V) Modeling

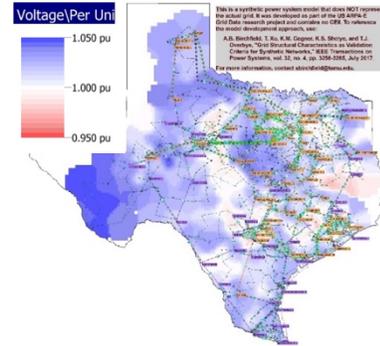


Figure 11, PV/PQ Voltage Contour

It is apparent that the three modeling methods each result in significantly different results. The voltage profiles and contingency results from steady state solutions, such as these, have the potential to affect system planning changes in a physical system. Inaccurate results during the planning stage could cause future system complications to go undetected. Although it is clear that each of the modeling methods have their differences, it is not yet clear which, if any, provide the most accurate results.

B. 2000 Bus Synthetic Texas Case

The 2000 bus synthetic Texas case, is overlaid onto a map of Texas and has a load profile which is similar to the actual state load. However, it is not representative of any physical grid system. Nevertheless, comparisons between steady state results from this system and the actual operating point of ERCOT’s system do have merit.

Figures 14 through 16 show the voltage contour for each of the models in the 2000 bus case. Again, these show more extreme voltages as each the voltage control model moves from PV/PQ to the linear Q(V) function, to the piecewise Q(V) function. Unfortunately, any most voltage information from ERCOT’s physical system is considered CEII (Critical Energy Infrastructure Information) and cannot be presented here. However, ERCOT does have a publicly available aggregate voltage profile, which is reproduced in Figure 17 below [10].

Figures 14 through 16 show the voltage profile of each of the synthetic cases, and Figure 17 shows ERCOT’s physical voltage profile. Comparison of ERCOT’s profile with each of the synthetic cases shows that the case using the linear Q(V) modeling method most closely resembles the physical system.

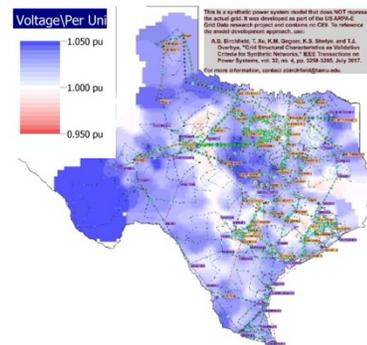


Figure 12, Setpoint Tolerance Voltage Contour

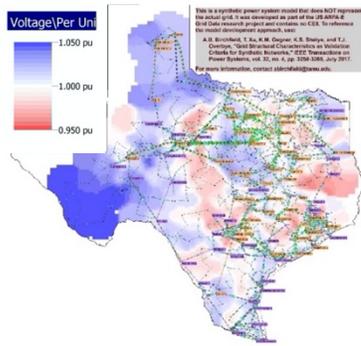


Figure 13, Droop Control Voltage Contour

2000-Bus Case Voltage Profiles

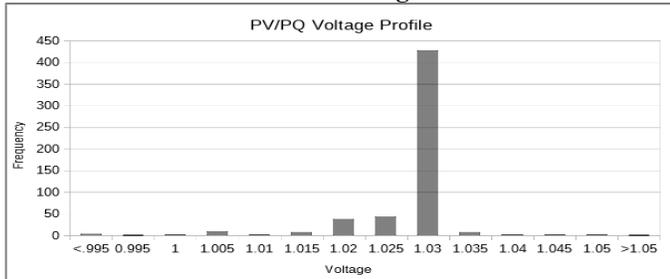


Figure 14: PV/PQ Modeling

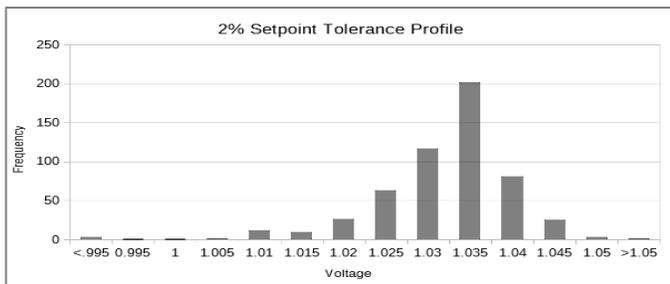


Figure 15: Linear Q(V) Modeling

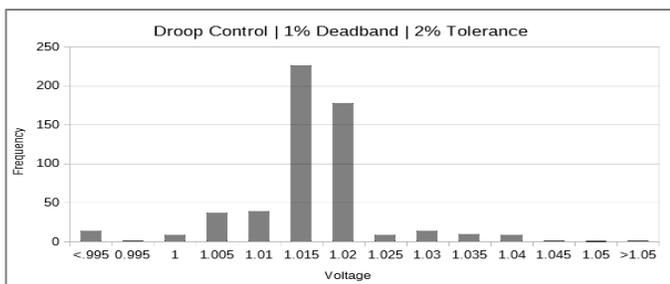


Figure 16: Piecewise Linear Q(V) Modeling

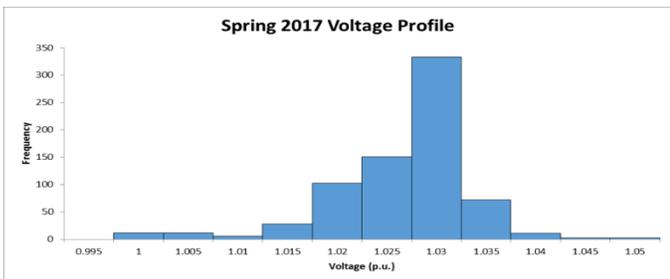


Figure 17, ERCOT Spring 2017 Voltage Profile [10]

Table 4: 2000 Bus Case Dynamic Reactive Reserves

Number of Generators	Low Q Limit	High Q limit	Total
PV/PQ	14	42	56
Linear Q(V)	0	11	11
Piecewise Q(V)	0	23	23

Table 4 shows the number of generators which are operating near one of their reactive power limits. Similar to the 200-bus case, the PV/PQ modeling method resulted in the most generators which operate at a reactive power limit.

The strictness of PV/PQ voltage regulation causes many generators to operate at one of their reactive limits. The linear function in the 0.02 setpoint tolerance case results in only 11 of 544 generators operating within 5% of the upper or lower limits. However, the Droop Control Case's deadband may be too "loose" leaving some generators without adequate support from their neighbors and several additional generators at their high limits.

C. 10,000 bus case

The final case considered is the 10,000-bus synthetic case which is overlaid on the Western United States. The voltage profiles, shown in Figures 18 through 20, illustrate the expected aggregate voltage response across the many buses. Dynamic reactive reserves results are shown in Table 5.

Table 5: 10,000 Bus Case Dynamic Reactive Reserves

Number of Generators	Low Q Limit	High Q limit	Total
PV/PQ	485	544	1029
Linear Q(V)	82	69	151
Piecewise Q(V)	96	60	156

10,000-Bus Case Voltage Contours

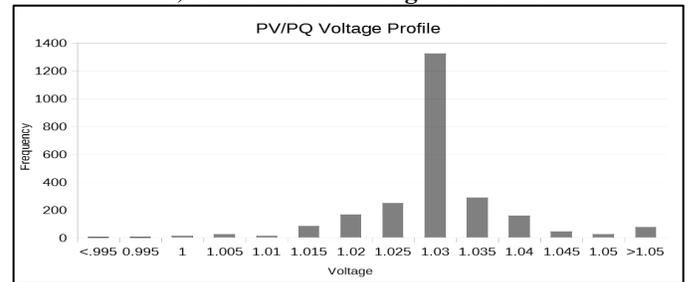


Figure 18 PV/PQ Modeling

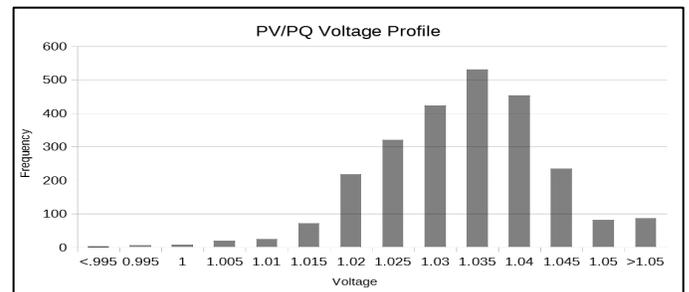


Figure 19: Linear Q(V) Modeling

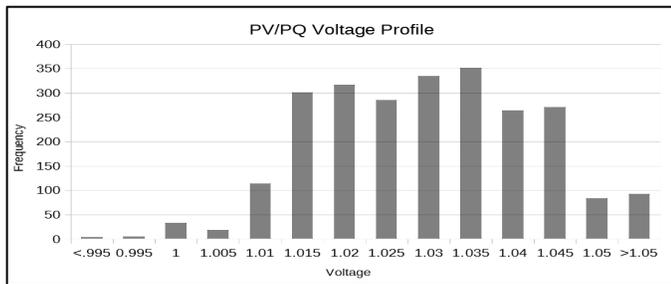


Figure 20: Piecewise Linear Q(V) Modeling

IV. CONCLUSION

Voltage Control plays an important role in any physical electric system's stability and sustained operation. Although it is not possible to perfectly model any physical system in a simulation, improvements to the current PV/PQ modeling method are possible. New modeling methods, such as the linear Q(V) and piecewise deadband Q(V) function methods presented here, have the potential to better represent a physical system.

Although all cases presented here are synthetic, the differences in the results from these cases are similar to the differences that would arise from using the three modeling methods on any simulated system. Ultimately, inaccurate results from steady state solutions, especially when related to planning studies for physical systems, will have consequences for the reliability of the grid which we depend on.

The results from the 2000 synthetic case show that the linear Q(V) method better represents an actual grid's voltage profile than the standard PV/PQ modeling method. This linear Q(V) method has the potential to improve simulation results in a wide variety of different systems.

V. ACKNOWLEDGMENTS

This work was partially supported through funding provided by the U.S. National Science Foundation in Award 1916142, US Department of Energy's (DoE) Cybersecurity for Energy Delivery Systems program under award DE-OE0000895, and the Texas A&M Smart Grid Center.

VI. REFERENCES

- [1] A.B. Birchfield, T. Xu, K. Gegner, K.S. Shetye, T.J. Overbye, "Grid Structural Characteristics as Validation Criteria for Synthetic Networks," *IEEE Trans. Power Systems*, vol. 32, pp. 3258-3265, July 2017
- [2] A. Birchfield, T. Xu and T. J. Overbye, "Power Flow Convergence and Reactive Power Planning in the Creation of Large Synthetic Grids," *IEEE Trans. Power Systems*, vol. 33, no. 6, pp. 6667-6674, Nov. 2018.
- [3] A. Capasso and E. Mariani, "Influence of Generator Capability Curves Representation on System Voltage and Reactive Power Control Studies," *IEEE Trans. Power App. and Sys.*, vol. PAS-97, no. 4, pp. 1036-1041, July 1978, doi: 10.1109/TPAS.1978.354582.
- [4] A. W. Azizan, V. K. Ramachandaramurthy and C. K. Loo, "The influence of embedded generator control modes on an electrical distribution network power flows and voltage profile," 2009 IEEE Bucharest PowerTech, Bucharest, 2009, pp. 1-7, doi: 10.1109/PTC.2009.5281867.
- [5] B. Allison, D. Wallison, T. Overbye and J. Weber, "Voltage Droop Controls in Power Flow Simulation," 2019 IEEE Texas Power and Energy Conference (TPEC), College Station, TX, USA, 2019, pp. 1-6.
- [6] D. K. Molzahn, V. Dawar, B. C. Lesieutre and C. L. DeMarco, "Sufficient conditions for power flow insolvability considering reactive power limited generators with applications to voltage stability margins," 2013 IREP Symposium Bulk Power System Dynamics and Control - IX

- Optimization, Security and Control of the Emerging Power Grid, Rethymno, 2013, pp. 1-11, doi: 10.1109/IREP.2013.6629370.
- [7] ERCOT.com, '2018_OTIS_Coordinated_Voltage_Control', 2020. [Online]. Available: http://www.ercot.com/content/wcm/training_courses/158273/2018_OTIS_Coordinated_Voltage_Control.pptx. [Accessed: 25- Apr- 2020].
- [8] ERCOT.com, "ERCOT Nodal Operating Guide", 2020. [Online]. Available: http://www.ercot.com/content/wcm/libraries/202570/March_1_2020_Nodal_Operating_Guide.pdf. [Accessed: 25- Apr- 2020].
- [9] ERCOT.com, "ERCOT Nodal Protocols", 2020. [Online]. Available: http://www.ercot.com/content/wcm/libraries/204209/April_3_2020_Nodal_Protocols.pdf. [Accessed: 25- Apr- 2020].
- [10] ERCOT.com, "ERCOT-NPRR_849_Overview", 2020. [Online]. Available: http://www.ercot.com/content/wcm/key_documents_lists/148053/ERCOT-NPRR_849_Overview.pptx. [Accessed: 25- Apr- 2020].
- [11] H. E. Brown, G. K. Carter, H. H. Happ and C. E. Person, "Power Flow Solution by Impedance Matrix Iterative Method," *IEEE Trans. Power App. and Sys.*, vol. 82, no. 65, pp. 1-10, April 1963, doi: 10.1109/TPAS.1963.291392.
- [12] J Adams, S. Sharma, S. H. Huang, C. Thompson, T. Mortensen, and E. A. Villanueva., "ERCOT ISO's experiences in handling voltage related issues in the control center," 2011 IEEE Power and Energy Society General Meeting, Detroit, MI, USA, 2011, pp. 1-4.
- [13] J. D. Weber and T. J. Overbye, "Voltage contours for power system visualization," *IEEE Trans. Power Systems*, pp. 404-409, February, 2000.
- [14] J. Glover, T. Overbye, and M. Sarma, *Power System Analysis and Design*, 6th ed. Boston, MA: Cengage, 2017.
- [15] M. Bjelogrić, M. S. Calović, P. Ristanović and B. S. Babić, "Application of Newton's optimal power flow in voltage/reactive power control," *IEEE Trans. Power Systems*, vol. 5, no. 4, pp. 1447-1454, Nov. 1990, doi: 10.1109/59.99399.
- [16] M. Okamura, Y. O-ura, S. Hayashi, K. Uemura and F. Ishiguro, "A new power flow model and solution method; Including load and generator characteristics and effects of system control devices," *IEEE Trans. Power App. and Sys.*, vol. 94, no. 3, pp. 1042-1050, May 1975, doi: 10.1109/TPAS.1975.31938.
- [17] NERC, "Reliability Guideline, Reactive Power Planning", 2016, Available: www.nerc.com/comm/PC_Reliability_Guidelines_DL/Reliability%20Guideline%20%20Reactive%20Power%20Planning.pdf [Accessed: 12- June- 2020].
- [18] R. D. Youssef, "Implicit generator and SVC modelling for contingency scheduling of reactive power dispatch," *IEE Proc. - Generation, Transmission and Distribution*, vol. 142, no. 5, pp. 527-534, Sept. 1995, doi: 10.1049/ip-gtd:19952044.
- [19] R. J. Brown and W. F. Tinney, "Digital Solutions for Large Power Networks," *Trans. AIEE, Part III: Power App. and Sys.*, vol. 76, no. 3, pp. 347-351, April 1957, doi: 10.1109/AIEEPAS.1957.4499563.
- [20] S. Khushalani, J. M. Solanki and N. N. Schulz, "Development of Three-Phase Unbalanced Power Flow Using PV and PQ Models for Distributed Generation and Study of the Impact of DG Models," *IEEE Trans. Power Systems*, vol. 22, no. 3, pp. 1019-1025, Aug. 2007, doi: 10.1109/TPWRS.2007.901476.
- [21] TAMU.edu, "Electric Grid Test Case Repository" 2020. [Online]. Available: <https://www.electricgrids.engr.tamu.edu>
- [22] W. - E. Liu, A. D. Papalexopoulos and W. F. Tinney, "Discrete shunt controls in a Newton optimal power flow," *IEEE Trans. Power Systems*, vol. 7, no. 4, pp. 1509-1518, Nov. 1992, doi: 10.1109/59.207375.
- [23] W. F. Tinney and C. E. Hart, "Power Flow Solution by Newton's Method," in *IEEE Trans. on Power App. and Sys.*, vol. PAS-86, no. 11, pp. 1449-1460, Nov. 1967, doi: 10.1109/TPAS.1967.291823.
- [24] WECC.org, 'Guide to WECC/NERC Planning Standards I.D: Voltage Support and Reactive Power', 2006. [Online]. Available: <https://www.wecc.org/Reliability/Voltage%20Stability%20Guide.pdf>. [Accessed: 12- May- 2020].
- [25] Y. Lei, R. Wang, T. Li, Q. Tang, Y. Wang and J. Li, "Modeling PV/PQ switching in security constrained optimal power flow," 2019 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia), Chengdu, China, 2019, pp. 84-88, doi: 10.1109/ISGT-Asia.2019.8881086.