Voltage Droop Controls in Power Flow Simulation

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***Abstract*— Steady state power flow simulation software is widely used across industry and academia for reliable system operation. Voltage regulation implementation in software typically makes use of PQ and PV buses separately resulting in an infinite slope QV curve, while units in industry typically have dead-bands and real sloped responses. In this work, a new technique for modeling power flow generator voltage control is implemented to more accurately model the real-world generator responses. The new technique has been compared with typical power flow control methods using a three-bus case study that portrays the differences in the two response types. The results obtained show that the new technique is more effective at modeling dead-bands and real sloped responses that exist in industry.**

***Keywords*— Voltage Droop Control, Automatic Voltage Regulation, power flow, Voltage Regulation**

I. Introduction

The use of steady state power flow simulation software has been growing in recent years, and its use in industry and research is ever prevalent. Due to their vast use, any software improvements which make for better representation of real systems have great value. Modeling and simulating voltage-controlled generators poses some challenges. One area that can use improvement is the model typically used for unit's voltage control. Despite knowing that units in industry typically use some method of droop control with a real slope and a dead-band, software typically implements an infinite slope QV curve with Min Q and Max Q "caps". This is due to programming complexities associated with the droop control methods that the proposed method attempts to solve.

Section II of the paper provides more background on current power flow modeling techniques, Section III portrays the methodology of implementing the new control method, Section IV presents a three-bus case study demonstrating the new controls, and, finally, Section V concludes the paper.

II. BACKGROUND

Voltage control is a fundamental requirement of operating any large-scale power system. Customers depend on the utility to provide power within an allowable voltage range, and voltage collapse or spikes can cause system instability. There have been many realistic synthetic power flow cases that have been created and widely used in research, including cases similar in size to the 3 interconnects present in the United States [5]. However, the realism of these cases is limited by the abilities of the power flow simulation software used. Simulation software usually implements voltage regulation using two types of buses: PV and PQ buses. At these buses, either real power and voltage, or real and reactive power are held constant, respectively. By default, all voltage regulated buses are PV buses and units at each bus hold voltage constant. Reactive power is solved for based on other constraints. When a user specified reactive power limit is violated, the bus is converted to a PQ bus, and reactive power is held constant at the limit, leaving voltage to vary. This implementation results in the green PQ curve shown in Fig. 1 and is deemed the Automatic Voltage Regulation or AVR method in this paper [8]. In industry, however, voltage control is accomplished by many discrete units, with different controls. Many of these units, such as windfarms [10], have dead bands and real sloped QV droop controls. A typical unit droop control can be seen in Fig. 1. The Electric Reliability Council of Texas (ERCOT), for example, does not specify any specific curve for units in its system. It only requires that units maintain the voltage within $\pm 2\%$ of their setpoint when not operating at their reactive capability limits. Thus, in ERCOT's system, any strictly decreasing curve within the $\pm 2\%$ range is acceptable; this is depicted in Fig. 1 [4]. In practice, this makes voltage less predictable, creating operational challenges that are not present in the currently available synthetic cases. Real world operators must handle voltage violations that show up unexpectedly and make real time adjustments, often manually switching reactive devices in or out or making unit adjustments. This experience would be beneficial to researchers if it were present in publicly available synthetic cases and simulation software, which would allow innovation of better reactive control methods.

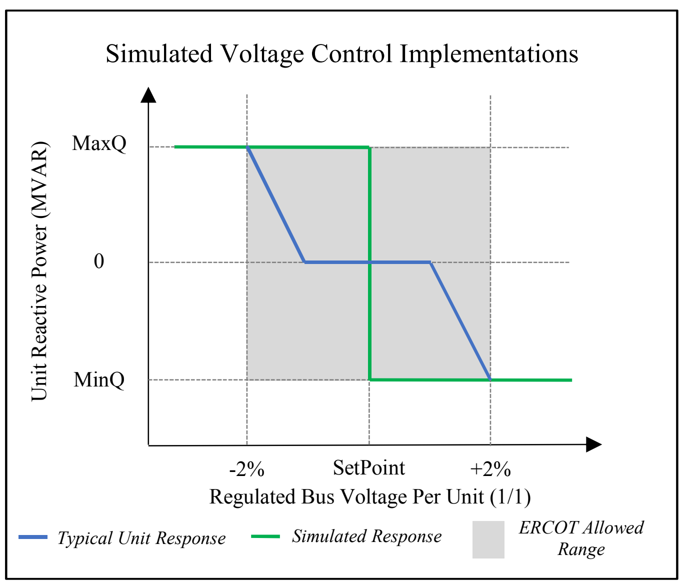

Fig. 1. A simulated Q(V) function and a typical industry Q(V) function

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Previous studies [9] have shown how voltage control devices can be implemented into simulation software. However, assumptions that are made to implement such controls, result in the green "Simulated Response" in Fig. 1 above.
In this paper, the methodology of simulating units with voltage droop controls is discussed. In these cases, units with voltage droop controls create challenges for finding solutions that are addressed in Section III.

III. Methodology

A. User Implementation

To better represent industry unit voltage response voltage droop controls are implemented, in the proposed method. Voltage Droop Controls can be added as a function for unit reactive output (Q) of voltage (V) at a specified "RegBus" or Regulated Bus. The function, denoted Q(V) here, is made up of five line segments, depicted below. Q_{min} and Q_{max} line segments, on the extreme ends, represent units that can no-longer decrease or increase their reactive power, and are similar to such segments in the Automatic Voltage Control method [8]. Droop controls for one or more generators can be added by users in the form of the following variables: Q_{max}, Q_{min}, Q_{db}, V_{high}, V_{low}, V_{dbhigh}, V_{dblow}. Each is defined as:

- Q_{max}: Unit Maximum Reactive Power Output
- Q_{min}: Unit Minimum Reactive Power Output
- Q_{db}: Unit Normal Reactive Power Output at nominal voltage (typically zero unless the unit model includes static reactive devices)
- V_{high}: Voltage above which unit will output Q_{min}
- V_{low}: Voltage below which unit will output Q_{max}
- V_{dbhigh}: Voltage above which unit begins to ramp down Q from Q_{db}
- V_{dblow}: Voltage below which unit begins to ramp up Q from Q_{db}

The resulting function is depicted in Fig. 2 below.

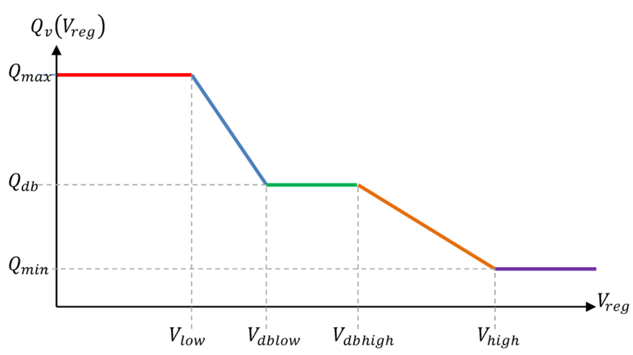

Fig. 2. Voltage Droop Control Q(V) function as defined by user

The new Voltage Droop Controls contrast with previous Automatic Voltage Regulation (AVR) implementation in that:

- In AVR implementation, either real power and voltage (A PV bus) are known, or real and reactive power are known for a bus (A PQ bus). From the known *static* elements, the other elements are solved for.
  Reactive power, in the Voltage Droop Control methodology is known as a function of some other voltage in the system and only power is known as static. (Such buses are deemed PQV buses in this paper and PowerWorld's notation). This introduces additional numerical complexities that must be dealt with.
- The Q(V) Voltage Droop Control function is continuous, but its derivative isn't. This makes it difficult to calculate derivatives for the Jacobian matrix. This is mitigated by smoothing the function using either a circular spline function or a cubic spline function.
- Multiple generators may regulate voltage at the same bus, each with similar or different control functions and may interfere with each other. This can lead to multiple steady state solutions.
- Low impedance branches between PQV buses and or PQ/PV buses that have different voltage control schemes may also introduce multiple or no steady state solutions due to different control schemes

More than one generator can be connected to one voltage control scheme. This is useful when multiple units are working together to regulate voltage at a single bus. In this case Q(Vreg) defines the total reactive power output of the entire group. The user defines a remote regulation factor (R_{XN}, where X is a voltage control group, and N is a unit number), that defines the participation percentage of each unit. Ideally, the user would set all of the R_{XN} regulation factors of the group to sum to 100%.

B. Voltage Droop Control and QV Characteristic Function

In order to mitigate issues caused by discontinuous derivatives, a smoothing function is applied to the Q(V) Voltage Droop Control function. This is done with either a cubic spline function or a circular spline function. The curve functions are both sufficiently close to the original function to limit variances in results. An example of such smoothing is shown in Fig. 3 below.

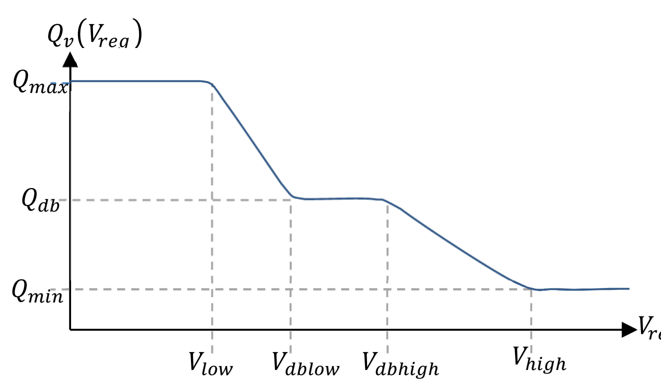

Fig. 3. Smoothed Q(V) function

C. *Generalized Voltage Droop Control*

This section addresses the challenge of finding solution for any system with multiple droop controls. Using the proposed method, voltages at regulated buses are calculated before voltages and reactive power contributions of the regulating units. However, we must first derive generator reactive power functions [G_Q(V)] and use them to calculate the Jacobian Matrix before we can run the power flow and determine the RegBus voltage. Generator contributions and bus voltages are then calculated using back substitution.

At any regulated bus, there may be a number of different voltage control schemes active including:

- Units operating under Voltage Droop Controls
- Units operating under AVR control
- Units operating at their Q_{min} or Q_{max} points (for either AVR or Voltage Droop Control) where this unit's bus becomes a PQ bus
- Units not providing any voltage support

These units may be connected directly to the bus or may be connected to a nearby bus. In order to simplify the algorithm and supporting documentation, units under AVR control regulating buses that are regulated by any Voltage Droop Control will be given an equivalent Voltage Droop Control for use in calculations at that bus. The AVR control curve is a specific case of the Voltage Droop Control curve so this can be easily done by setting:

$$V_{low} = V_{dblow} = V_{dbhigh} = V_{high} = V_{setpoint}$$

The notation throughout the rest of this paper, the reactive power contributions of each group are denoted as follows:
For a unit N regulating voltage at a bus b within Voltage Droop Control Groups A and B:

G_{qAN}: Part of Voltage Droop Control with output between Q_{min} and Q_{max}
G_{qANoff}: Part of Voltage Droop Control, but AVR is set to [OFF], or unit is stuck at Q_{min} or Q_{max}. Unit operating with constant reactive power
G_{qNnone}: Unit is not part of Voltage Droop Control
$G_{qBN,}$, G_{qBNoff}

G_q is used here for the reactive power output of a generator to differentiate it from Q, which is reserved for bus level reactive power export and is present in power flow calculations.

The three regulation groups are shown in Figs. 4-6 below.

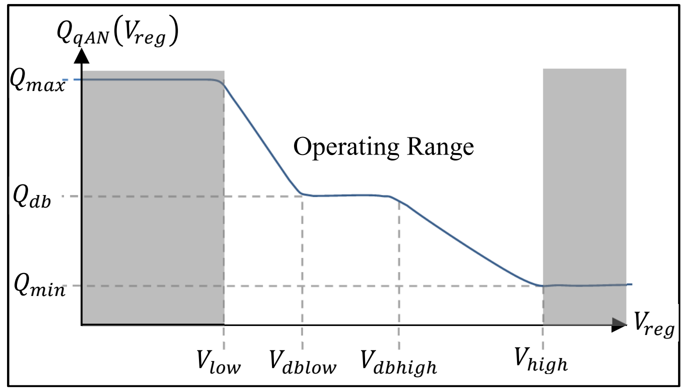

Fig. 4. Q (Vreg) for units on Voltage Droop Control

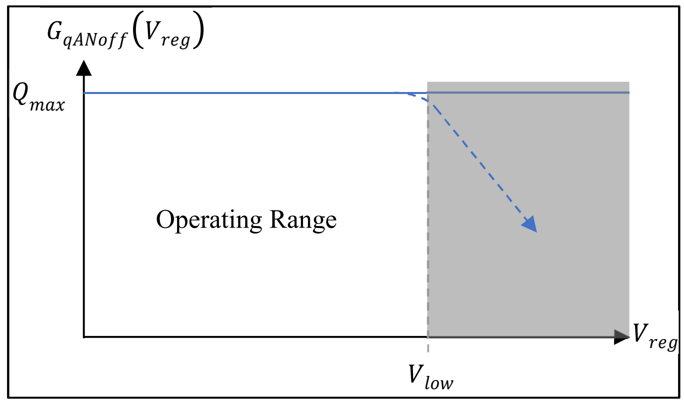

Fig. 5. Q (Vreg) for units operating at reactive power limits

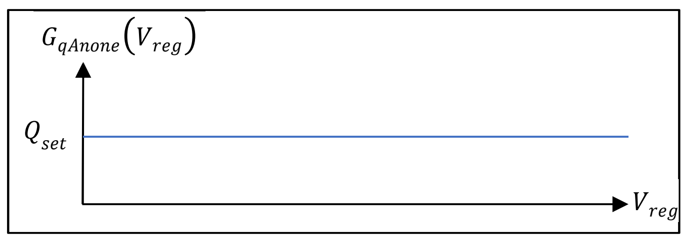

Fig. 6. Q (Vreg) for units without voltage regulation

For units operating with Voltage Droop Control on the G_{qAN}(Vreg) function, the algorithm will change the function to a G_{qANoff}(Vreg) type function if the voltage exits the operating range. This will occur on the next iteration of the voltage control loop. The same concept applies for units operating on the G_{qANoff}(Vreg) function that exit the operating range. This covers the unit level reactive power functions; however, these must still be incorporated into the power flow.

D. Voltage Droop Control

To derive the later equations, the one line below is given in Fig. 7.

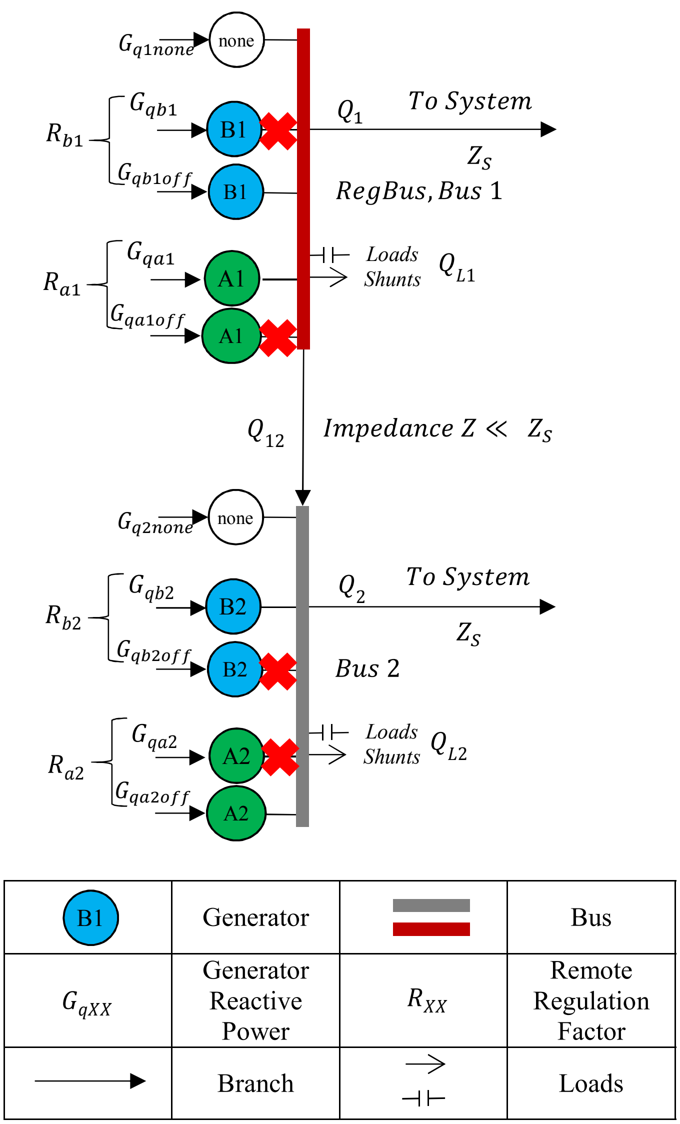

Fig. 7. Example One-Line

Fig. 7 above gives a one-line example of a Voltage Droop Control setup. Only reactive power is modeled and shown. Present in Fig. 7 are two buses (1 and 2) and two voltage control groups (A and B). Bus 1 is designated as the "RegBus" for both control groups and all reactive powers part of either Voltage Droop Control are a function of the voltage at this bus.

E. RegBus Equations

At the RegBus, a function $G_Q(V)$ must be derived for each generator from the $Q_v(V_{reg})$ function given by the user. The example in this paper uses control groups A and B. Assume that there are 2 Units connected within each control group A and B.

We define the $Q(V_{reg})$ function such that the reactive power contributions from each generator must sum to the total droop control result.

$$Q_{va}(V_{reg}) = G_{qa1} + G_{qa1off} + G_{qa2} + G_{qa2off} \quad (1)$$

$$Q_{vb}(V_{reg}) = G_{qb1} + G_{qb1off} + G_{qb2} + G_{qb2off} \quad (2)$$

Here G_{qa1} and G_{qa1off} are exclusive, and only one is non-zero. The $Q_{va}(V_{reg})$ function is specified by the user, and will need to be enforced. Therefore, it is necessary to describe how each of the generators in the droop control share the responsibility to regulate voltage. For this, the algorithm employs remote regulating factors (R_{xx}) for each Voltage Droop Control object. Each factor represented as unit reactive power equals a percentage multiple of droop control group reactive power. Note that G_{qAnone} and G_{qBnone} are not present in the droop control equations and not considered in the droop control. The remote regulation factors are applied, in general, as below:

$$G_{qa1} = R_{a1} * Q_{va}(V_{reg}) \quad (3)$$

To further simplify computation and mitigate end-user addition issues (where $R_{a1}+\ldots+R_{aN} \neq 1$), normalized factors ($K_{XX}$) are used in the balancing equations. If there are 4 units 1 through 4 within Voltage Control Group [A] then:

$$K_{a1} = \frac{R_{a1}}{R_{a1}+R_{a2}+R_{a3}+R_{a4}} \quad (4)$$

The K values are modified to omit reactive power contributions from generators that have hit their Mvar limits. If units 2 and 4 are operating at their Mvar limits then:

$$K_{a1} = \frac{R_{a1}}{R_{a1}+R_{a3}} * \left(1 - \frac{R_{a2}+R_{a4}}{R_{a1}+R_{a2}+R_{a3}+R_{a4}}\right) \quad (5)$$

Equation 3 above is then rewritten as:

$$G_{qa1} = K_{a1} * Q_{va}(V_{reg}) \quad (6)$$

F. Regulated Bus Equation Derivation

The Mismatch equations at Bus 1 and 2 are known to be:

$$-Q_1 - Q_{L1} + G_{q1none} + G_{qb1} + G_{qb1off} + G_{qa1} + G_{qa1off} - Q_{12} = 0 \quad (7)$$

$$-Q_2 - Q_{L2} + G_{q2none} + G_{qb2} + G_{qb2off} + G_{qa2} + G_{qa2off} + Q_{12} = 0 \quad (8)$$

And in general:

$$-Q_1 - Q_{L1} + G_{q1none} + G_{qb1} + G_{qb1off} + G_{qa1} + G_{qa1off} -Q_2 - Q_{L2} + G_{q2none} + G_{qb2} + G_{qb2off} + G_{qb2} + G_{qa2off} = 0 \quad (9)$$

However, G_{Qa1} type equations are not used in the power flow calculation, and Q must be calculated in other terms. Recall from above:

$$G_{qa1} = K_{a1} * Q_{va}(V_{reg}) \quad (6)$$

Substitution of the related formulas gives:

$$-Q_1 - Q_{L1} + G_{q1none} + K_{b1} * Q_{vb}(V_{reg}) + G_{qb1off} +$$

$$K_{a1} * Q_{va}(V_{reg}) + G_{qa1off} - Q_{12} = 0 \tag{10}$$

Here Q_1 is already calculated in previous power flow calculations and all other terms are constant or a function of V_{reg}. Bus 2 needs special treatment as well, even though it is not the RegBus.

$$-Q_2 - Q_{L2} + G_{q2none} + K_{b2} * Q_{vb}(V_{reg}) + G_{qb2off} + K_{a2} * Q_{va}(V_{reg}) + G_{qa2off} + Q_{12} = 0 \tag{11}$$

Such treatment applies for all buses connected to any RegBus.

G. Derivation Terms for the Jacobian Matrix

The derivative of the Q terms is straightforward as follows. Modifications must be made to the Jacobian for all buses in a voltage droop control as well as any arriving branch: in the control.

$$-\frac{dQ_1}{dx} - \frac{dQ_{L1}}{dx} - \frac{dQ_{12}}{dx} + K_{b1} * \frac{dQ_{vb}(V_{reg})}{dx} + K_{a1} * \frac{dQ_{va}(V_{reg})}{dx} \tag{12}$$

$$-\frac{dQ_2}{dx} - \frac{dQ_{L2}}{dx} + \frac{dQ_{12}}{dx} + K_{b2} * \frac{dQ_{vb}(V_{reg})}{dx} + K_{a2} * \frac{dQ_{va}(V_{reg})}{dx} \tag{13}$$

IV. Case Study

To demonstrate the new Voltage Droop Controls, a 3-bus test case is created. Its one-line is shown in Fig. below.

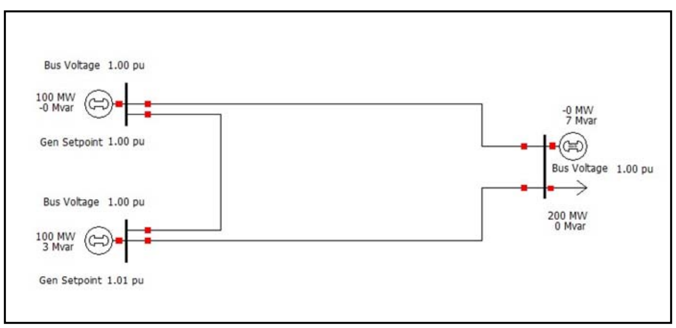

Fig. 8. One Line of case study

Buses 1 and 2 on the left are closely connected with a low impedance line (X = .001 pu), and each is connected to the load, bus 3, with a longer line (X = .05 pu). It is supposed that, despite their close proximity, units 1 and 2 did not coordinate voltage control and are set to setpoints 1.00 pu and 1.01 pu respectively. Here the slack unit at bus 3 is used as a variable reactive power load by adjusting its set-point and the 200MW load remains constant. The units are first set to Automatic Voltage Regulation and results are observed in figure 9.

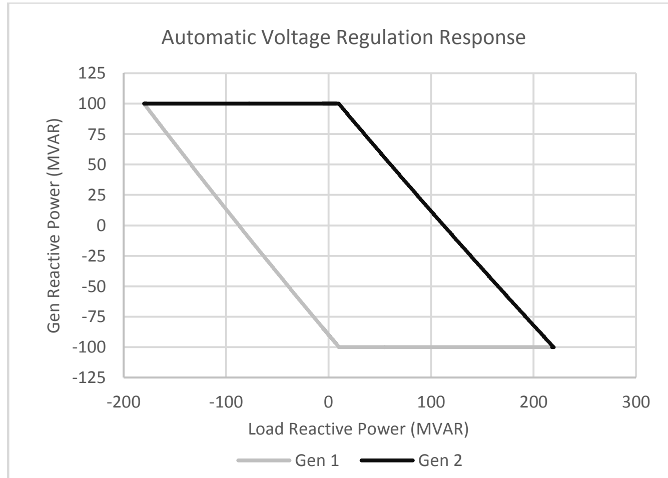

Fig. 9 AVR voltage control response of units 1 and 2

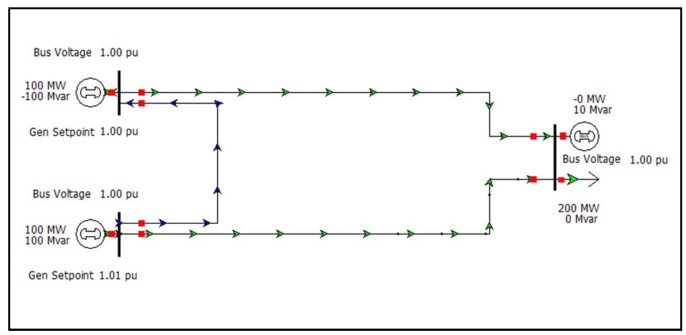

Fig. 10. One Line of case study with generator interference

Because of its lower setpoint, unit 2 ramps up long before unit 1 begins supporting the voltage. At one point, near 0 MVAR load, the units counter each other's outputs. This effect is shown in more detail on the one line in Fig. above.

In a case with real losses, this would increase system costs without preforming any real work. It is well known that such a situation should be avoided, but it is not widely known if this occurs in industry often. To better understand how a system with droop controls would respond, the units are switched to Voltage Droop Control. The parameters are set based on a $\pm 0.5\%$ deadband and a $\pm 2\%$ swing range and are recorded in Table I below. The results of the study are shown in Fig. 8 below.

TABLE I
Case Study Voltage Droop Control Settings

	Qdb	Qmax	Qmin	Vlow	Vdblow	Vdbhigh	Vhigh
Gen 1	0	100	-100	0.98	0.995	1.005	1.02
Gen 2	0	100	-100	0.99	1.005	1.015	1.03

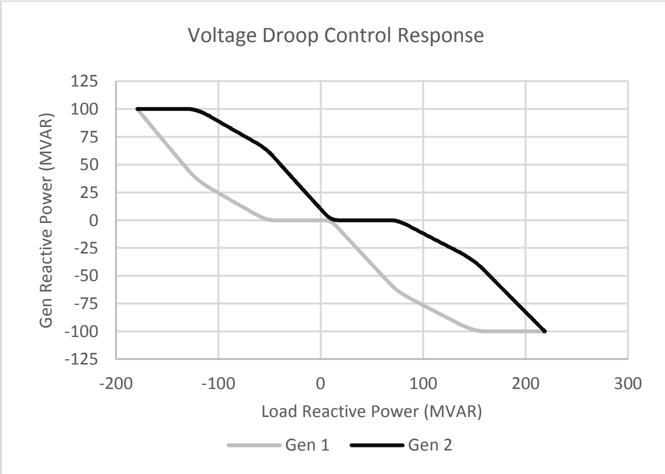

Fig. 8. Voltage Droop Control response of units 1 and 2

It can be seen that even with different “setpoints”, units with wide responses within their Voltage Droop Controls will “share” reactive power support. It has been shown that the Voltage Droop Control model is a more accurate representation of industry units [10], bit little previous work has been done a system wide response to such a model. Figs. 9 and 11 show that system responses are sufficiently different to warrant investigation. Because of its prevalence in industry and the difference between the Voltage Droop Control model and AVR model, further research using the Voltage Droop Control method is essential.

V. , CONCLUSION

In this paper, a new technique for modeling power flow generator voltage control using voltage droop controls has been studied, and a derivation of the calculation modifications made to support the function have been shown. The problems with simulating voltage control using previous methods are addressed and improved in the method demonstrated in this paper. The droop control feature is essential for creating simulations of power flow systems that more accurately model industry voltage-controlled generators. An example case is given that demonstrates the differences in the system response between using the automatic voltage control method (AVR) and the voltage droop control method. Future work will include implementing voltage droop controls into a large synthetic case such as the 10000-bus case described in [5].

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