21, rue d'Artois, F-75008 PARIS
http: //www.cigre.org

CIGRE US National Committee
2022 Grid of the Future Symposium

Optimal Volt-VAR and Frequency-Watt Inverter Settings in an Islanded Microgrid

A. JAIN, N. GURUNG, H. ZHENG
Commonwealth Edison Company
USA

SUMMARY

ComEd has installed the Bronzeville Community Microgrid (BCM) on Chicago's South Side. It is a crucial technological step as it adds substantial value to the community by making the power supply more reliable, resilient, and sustainable. However, there are certain challenges associated with microgrids operation like fluctuations in voltage and frequency, especially in islanded mode. DER smart inverters have grid voltage and frequency support capabilities and are expected to mitigate microgrid voltage and frequency fluctuations due to sudden changes in load and transition between different modes. In this paper, optimal smart inverter settings for volt/var and frequency/watt control in battery energy storage systems and solar photovoltaic are explored specifically for BCM. The efficacy of the proposed inverter control settings in mitigating voltage and frequency fluctuations is tested under three cases. It is shown that with the proposed inverter control, the system's dynamic response is improved, more robust, and the oscillations damp out faster.

KEYWORDS

Microgrid, Battery Energy Storage System, Solar Photovoltaic, Droop Control, Gas Generator, Islanded Microgrid, Smart Inverter, Volt/VAR, Frequency droop

niroj.gurung@comed.com

INTRODUCTION

As of 2021, the Department of Energy database [1] lists 676 operational microgrids in the United States producing a combined 4.13 GW of electricity. These numbers are expected to grow as more utilities, commercial entities, and university campuses are seeking to leverage the advantages of microgrids (MG) which include integration of distributed renewable generation, improved resiliency, reliability, and ability to island in case of grid outages. ComEd, as a leading utility, is commissioning the Bronzeville Community Microgrid (BCM) on Chicago's South Side. The BCM also connects to the neighboring Illinois Institute of Technology (IIT) campus microgrid, creating the nation's first utility-operated microgrid cluster.

Although microgrids have many advantages, there are several challenges as well, especially in islanded mode of operation. When connected to the grid, generators within the microgrid operate in the grid following mode and the high inertia synchronous generators regulate the grid frequency. Similarly, grid level reactive power compensation devices regulate voltage and prevent large voltage fluctuations. However, when islanded, microgrids have significantly lower inertia. The issue is more pronounced in microgrids with inverter-based resources (IBR) such as solar PV and battery energy storage systems (BESS). In such systems, large frequency and voltage fluctuations may occur due to load changes or sudden changes in generation in the case of PV.

Earlier grid standards such as IEEE 1547-2003 required IBRs to disengage/disconnect during disturbances as the total power contribution from the IBRs was relatively insignificant during those years. As the amount of IBRs have increased significantly in last couple of decades, the grid operators realized the need for the grid support functionalities from IBRs specially during grid disturbance events. This has led to updates in grid code requirements and interconnection standards for IBRs. For example, the latest IEEE 1547-2018 [2] standard mandates DER participation in grid voltage and frequency regulation with specified droop functions and allowable range of settings. The standard explicitly allows intentional islanding of microgrids while requiring DERs to provide active, reactive power support for frequency and voltage regulation. The standards, however, still do not explicitly mention the requirements for IBRs in islanded microgrid operation.

Academic literature is replete with various solutions for voltage and frequency regulation in microgrids. In addition to droop-based solutions [3], secondary supervisory control implementations [4], [5] and communication-based coordinated control strategies [6] have also been proposed. However, actual implementation of such solutions is limited by regulations and grid codes. Therefore, this study aims to identify optimal volt/var and frequency/watt droop settings to mitigate voltage and frequency fluctuations in islanded microgrid strictly within the purview of IEEE 1547-2018 standard. The study is based on ComEd's Bronzeville Community microgrid (BCM) model. Specifically, different volt/var and frequency/watt droop settings are considered for available inverter based DERs and their impact on frequency and voltage fluctuations during intentional islanding and load change scenarios is studied and compared.

SYSTEM MODEL: BRONZEVILLE COMMUNITY MICROGRID

The single line diagram of BCM is shown in Fig. 1. It consists of two 12 kV distribution feeders categorized as subsystem 1 (SS-1) and subsystem 2 (SS-2). The top feeder SS-1 is connected to the grid via POI-1 switch. The subsystem SS-1 has a 4.8 MW gas generator, a utility scale 500 kW/2000 kWh BESS unit, and a 750 kW solar PV station. In addition, there are distributed loads and distribution automation (DA) devices. SS-2 is connected to the grid upstream via POI-2 switch and it only consists of distribution loads and DA devices. The two subsystems can be interconnected via tie-switches T1, T2, or T3. When interconnected the total peak load in BCM is approximately 7 MW.

In grid-connected mode, both POI switches are closed and the three DERs present in BCM operate in grid-following mode to provide grid support. However, in case of abnormal conditions at the point of interconnection, BCM has the ability to island itself. When islanded, the gas generator operates in isochronous mode, and the BESS and solar PV operate in grid-following mode.

BCM can be fully or partially islanded depending on the status of the connection switches. Since all the DERs are part of SS-1, BCM can be partially islanded by opening POI-1 and keeping the three tie-switches at open position. To fully island BCM, subsystems SS-1 and SS-2 are first interconnected via one of the three tie-switches. Subsequently, SS-2 is disconnected from the main grid by opening POI-2 switch. At this point the loads connected to the feeder 2 are supplied partially by the DERs in SS-1 and the main grid. The DERs are ramped up to fully meet the load requirements such that power flow through POI-1 is insignificant. At this point, SS-1 is disconnected from the main grid by opening POI-1 switch. However, in case of an unplanned islanding due to abnormal grid conditions, POI-1 may be disconnected before power balance is achieved. Even in such a scenario, however, it is ensured that the DERs are capable of meeting the load demand.

The microgrid dynamic model was developed and simulated under various scenarios using Real Time Digital Simulator (RTDS).

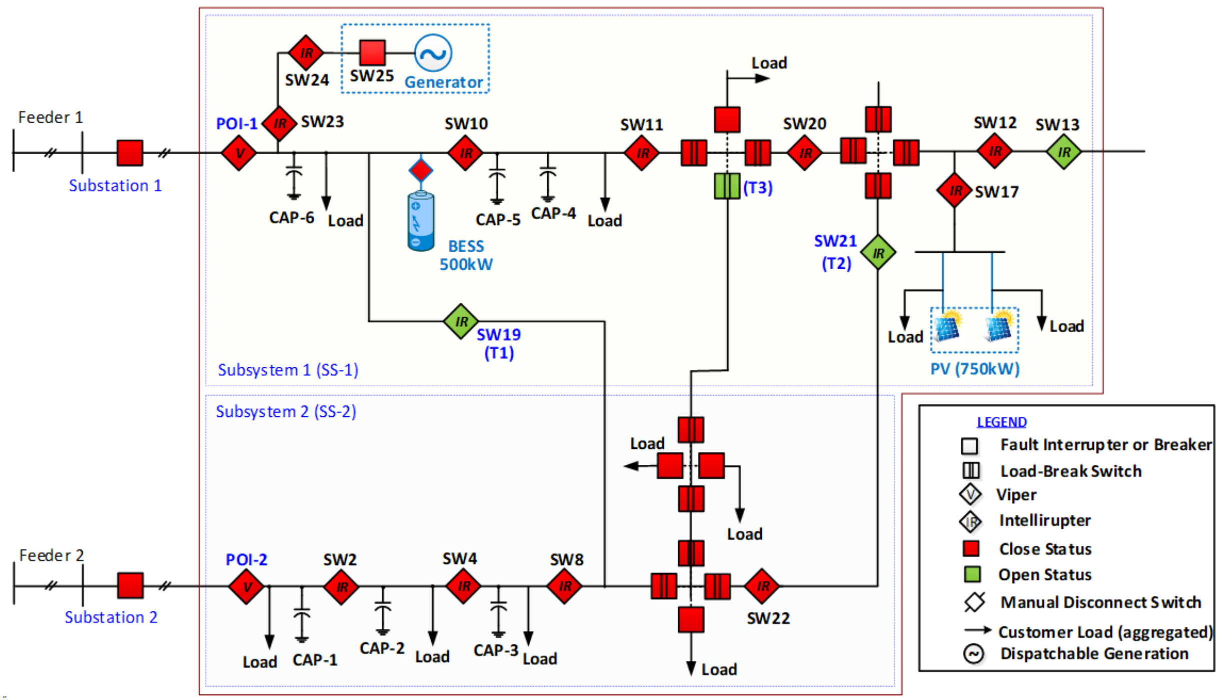

Figure 1 : Single line diagram of Bronzeville Community Microgrid

CHALLENGES IN ISLANDED MICROGRIDS

Some of the key challenges of microgrid operation in an islanded mode are:

1. Fluctuations during islanding: During islanding, fluctuations in voltage and frequency occur due to mismatch between DER generation and load requirement. In planned islanding, this situation can be largely avoided. Frequency fluctuations may still occur in planned islanding as frequency regulation task shifts from the grid to the isochronous generator and any delay introduced in transmitting the status of the POI switches to the generator controller before it switches its mode from grid following mode to an isochronous mode. Unplanned islanding can cause large voltage and frequency fluctuations as there will be large mismatch between the load and generation during the island formation.

2. Fluctuations due to load changes: When the system load or DER generation changes suddenly, voltage and frequency fluctuations may be observed. In the case of the BCM, for a sudden load change, the isochronous gas generator is required to respond and regulate frequency. Depending on the frequency governor's response time, fluctuations are seen. The mechanical inertia of the gas generator's rotor does mitigate fluctuations to a certain extent but may not be sufficient for large load steps. Similarly, reactive load changes may also cause voltage fluctuations. With frequency/watt and volt/var control, inverter based DERs will respond to fast load changes and largely mitigate frequency and voltage fluctuations.

SMART INVERTER CONTROL TO MITIGATE VOLTAGE AND FREQUENCY FLUCTUATIONS

IEEE 1547-2018 has defined various smart inverter functions for enabling grid support and ride through capabilities of inverter-based grid integrated DERs. In this work, two key functions are explored further with objective of identifying optimal settings for the inverters in microgrids to support voltage and frequency and enhance the microgrid operational robustness.

1. Frequency/Watt Control: For temporary frequency fluctuations outside the deadband, smart inverters are required to adjust their active power output in response to fluctuations. When PCC frequency is below the deadband's lower limit, BESS and solar inverters inject active power. Similarly, for PCC frequencies beyond the deadband's upper limit, the DER inverters respond by reducing the active power output. BESS resources are capable of absorbing active power if necessary. The magnitude of active power response is determined by the droop function values as shown in Table 1, where P_{pre} is the power output before disturbance. And P_{UF} and P_{OF} are active power output based on the droop settings in the inverter, in response to a disturbance in the system.

Four different droop curves corresponding to the range of allowable settings specified in [2] are shown in Fig. 2. For droop A and droop B a frequency deadband (db) of 0.036 Hz is considered. Whereas, for droop C and droop D a frequency db of 0.017 Hz is considered. The droop slopes k_{UF}/k_{OF} for droop A – D are 0.05, 0.03, 0.05, and 0.03 respectively.

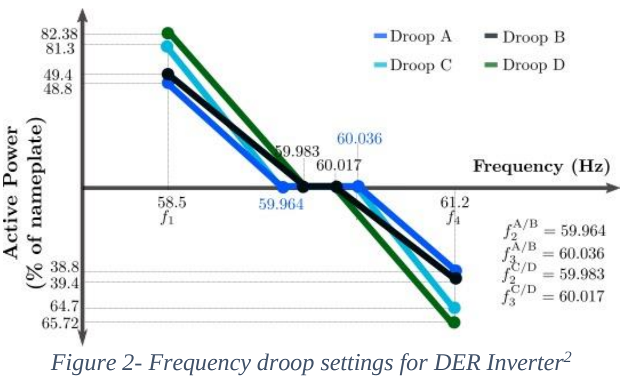

Figure 2- Frequency droop settings for DER Inverter[2]

Table 1- Frequency droop settings considered for DER smart inverter

f_i	**Range of Freq (Hz)**	P_i
f_1	58.5	$P_{pre} + P_{UF}$
db_{UF} f_2	59.964-59.983	0
db_{OF} f_3	60.017-60.036	0
f_4	61.2	$P_{pre} + P_{OF}$

2. Volt/VAR Control: Analogous to frequency/watt control, to mitigate voltage fluctuations, the smart inverters are required to provide var compensation in proportion to the magnitude of fluctuation as per [2]. The corresponding general volt/var droop function is shown in Fig. 3. The standard further specifies the droop function values for category A and B systems. For this study, the more stringent category B requirements are considered. Table 2 specifies the various droop settings considered in this study.

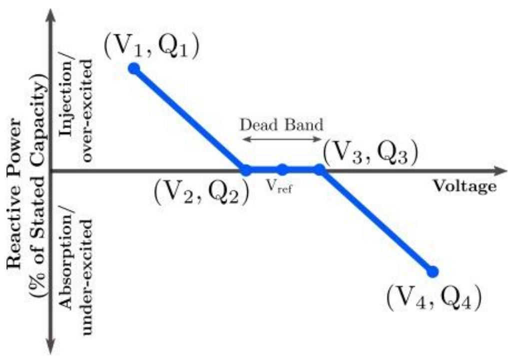

Figure 3: Voltage reactive power characteristics

Table 2- Voltage droop settings considered for DER smart inverter

	Droop A		Droop B		Droop C		Droop D	
V_i	**V (pu)**	Q_i	**V (pu)**	Q_i	**V (pu)**	Q_i	**V (pu)**	Q_i
V_1	0.92	44% S_{rated}, inject	0.92	70% S_{rated}, inject	0.92	44% S_{rated}, inject	0.92	70% S_{rated}, inject
V_2	0.98	0	0.98	0	0.99	0	0.99	0
V_3	1.02	0	1.02	0	1.01	0	1.01	0
V_4	1.08	44% S_{rated}, absorb	1.08	70% S_{rated}, absorb	1.08	44% S_{rated}, absorb	1.08	70% S_{rated}, absorb

RESULTS and DISCUSSION

The voltage-reactive power and frequency-active power droop functions/characteristics are configured within the allowable range specified in IEEE 1547-2018 std. The implementation of these functions during intentional islanding (both planned and unplanned) and during load change is studied for various scenarios discussed below.

Case 1: Step Increase in Load during Islanding

In this case, the MG is in islanded mode and to study system response under load change, at t = 0.5 sec a sudden increase in load is introduced. System response without droop and with different combinations of voltage and frequency droop settings are analyzed. Specifically, 2 values each of deadband and droop slopes and their combinations are considered. The droop values corresponding to the scenario with the best performance are used in further analysis. From Fig. 4, it can be seen that with the proposed droop control the oscillation in frequency and voltage damp out faster, and in addition their transient peak decrease. In frequency waveform without frequency/watt droop the frequency response has a transient peak of 60.4226 Hz i.e., 0.4226 Hz above nominal. This deviation from the nominal is reduced with droops A – D by approximately 40.8%, 61.73%, 43.63%, and 63.64% respectively. Similarly, for the voltage waveform, the transient peak without droop is 0.976 pu, which with droops A – D is improved to 0.98 pu, 0.982 pu, 0.983 pu and 0.986 pu, respectively. It can be concluded that droop D has the best performance and will be used for further studies.

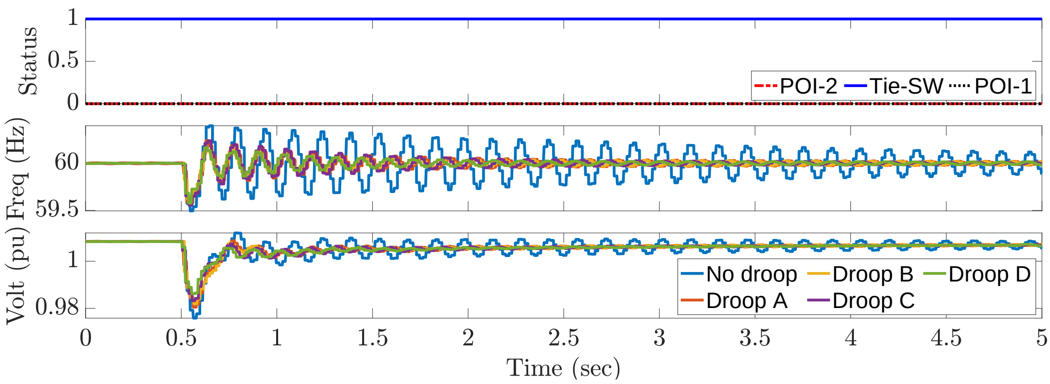

Figure 4: Case 1-system response at generator POC without and with different droop settings

Frequency and voltage waveform at BESS and solar PV POC is shown in Fig. 5.

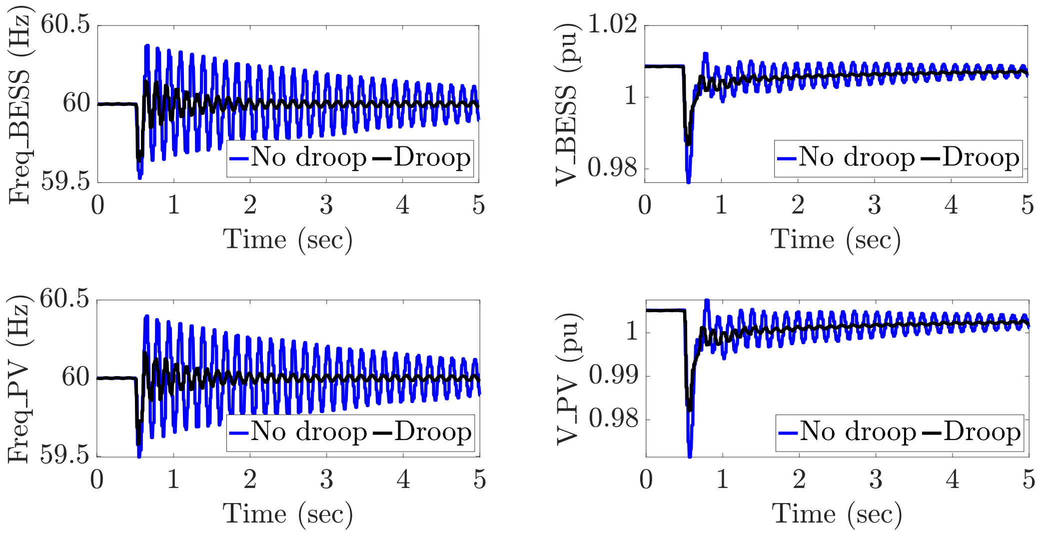

Figure 5: Case 1-voltage and frequency without and with proposed droop control

Case 2: Step decrease in load during Islanding

For this test case, in an islanded MG, a sudden decrease in load is introduced at t = 0.5 sec. System response without and with proposed volt/var and frequency/watt droop control is shown in Fig. 6. The frequency response transient peak reduces by approximately 14%. And the voltage transient peak improves from 1.054 to 1.04 pu for generator, from 1.054 to 1.041 pu for BESS, and from 1.05 to 1.038 pu for PV. It can be concluded that with the proposed droop, the frequency and voltage transients damp out faster and their magnitude is smaller.

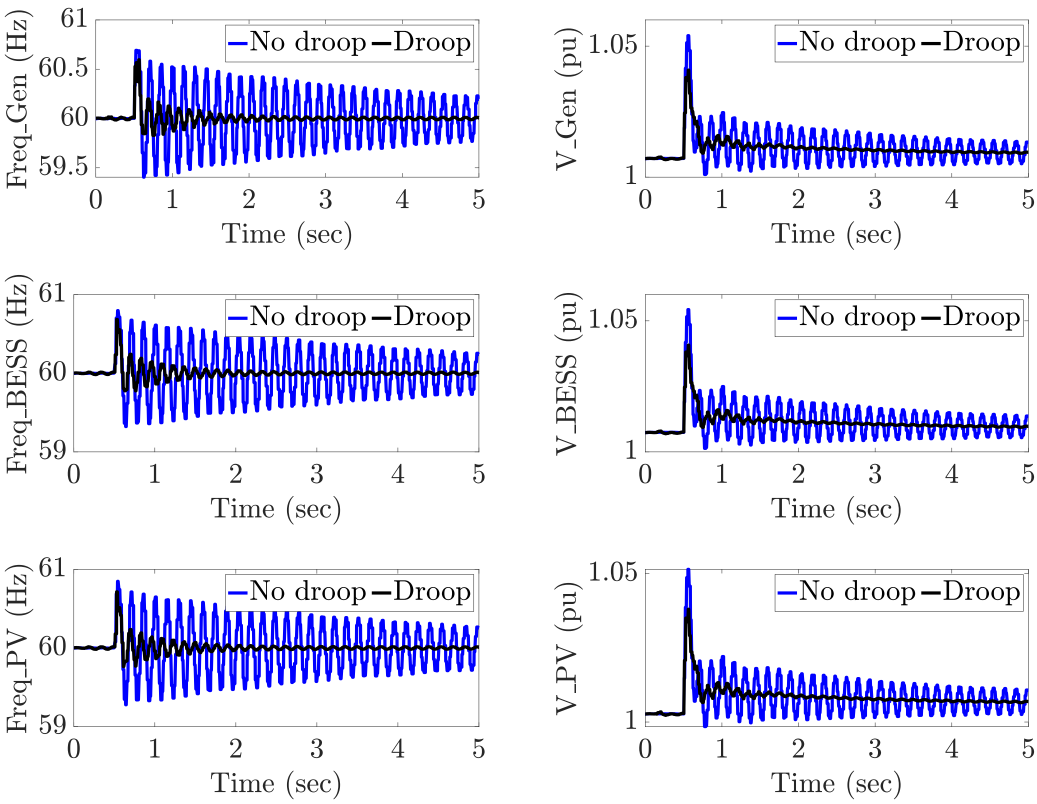

Figure 6: Case2-voltage and frequency without and with proposed droop control

Case 3: Unplanned Islanding

In case of detection of a disturbance near POI the BCM disconnects itself from the main grid and transitions into islanding mode. Since the active and reactive power at the POI-1 before islanding are positive, the load in the MG is more than generation. Therefore, at the instant of islanding there is a dip in frequency and voltage. It is important to note that the ramp rate of the generator is relatively slow compared to BESS and solar. Thus, as soon as the system is islanded the voltage and frequency droops act to curb the fluctuations resulting in improvement in system response compared to no droop case. In addition, the response is more robust as the oscillation damp out faster. Fig. 7 shows the results for this test case.

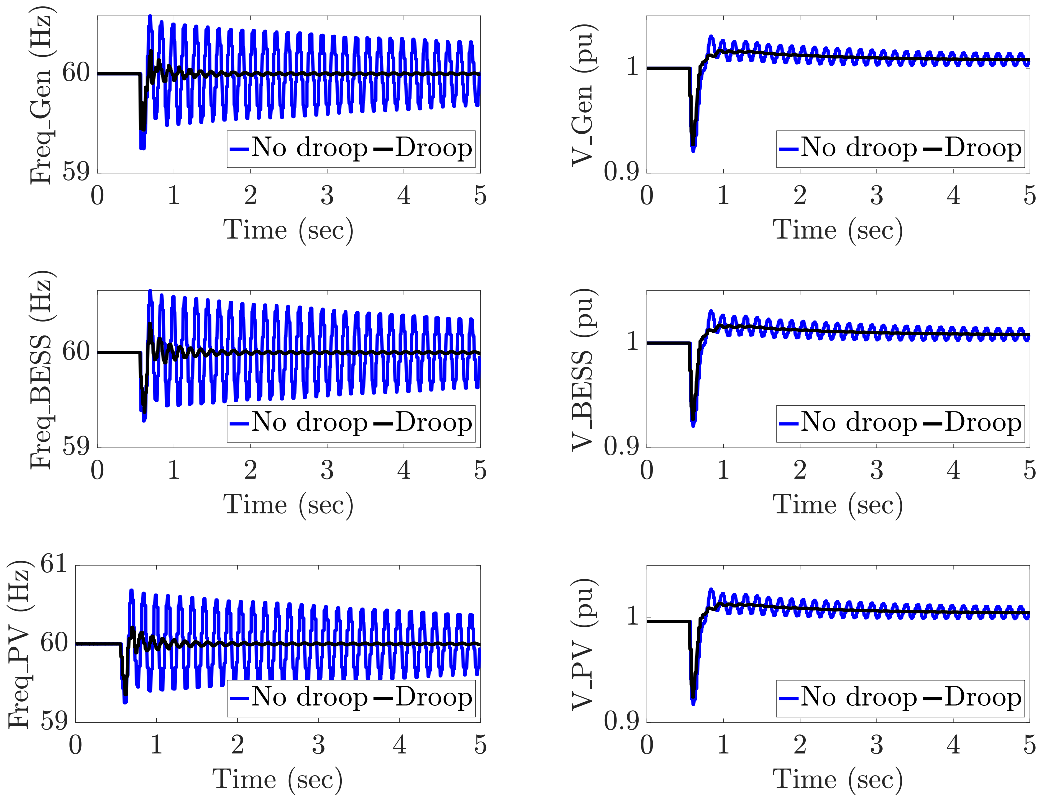

Figure 7: Case3-voltage and frequency waveforms without and with proposed droop control

CONCLUSION

The main goal of this study was to identify optimal volt/var and frequency/watt droop settings for DER smart inverters to mitigate voltage and frequency fluctuations in islanded microgrid under the purview of IEEE 1547-2018 standard. The study is based on ComEd's Bronzeville Community microgrid (BCM) model. Specifically, different volt/var and frequency/watt droop settings were considered for available inverter-based DERs and their impact on voltage and frequency fluctuations during intentional islanding and load change scenarios was studied and compared. Based on the system response with different settings, the optimal volt/var and frequency/watt droop settings was selected for BCM. The efficacy of the proposed inverter droop control was validated under three different cases. With the proposed droop control, the system response is robust, the transient peaks and drops in voltage and frequency are reduced, and the generators' voltage and frequency oscillations are damped faster. The results show the importance of optimally selecting the smart inverter settings for enabling robust and stable microgrid operation especially during the transition period and islanded mode operation when the system inertia is significantly reduced.

BIBLIOGRAPHY

[1] May,2021, "The Microgrid Installation Database," U.S. Department of Energy. [Online]. Available: https://doe.icfwebservices.com/microgrid

[2] "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, doi: 10.1109/IEEESTD.2018.8332112.

[3] H. R. Pota, "Droop control for islanded microgrids," *2013 IEEE Power & Energy Society General Meeting*, 2013, pp. 1-4, doi: 10.1109/PESMG.2013.6672541.
[4] M. Schifani, E. Waffenschmidt and R. Iravani, "Supervisory control of microgrids in grid-connected and islanding mode — Investigations using a real-time digital simulation platform," *2017 International Energy and Sustainability Conference (IESC)*, 2017, pp. 1-9, doi: 10.1109/IESC.2017.8167485.
[5] J. Lee, Y. Kim, and S. Moon, "Novel Supervisory Control Method for Islanded Droop-Based AC/DC Microgrids," in *IEEE Transactions on Power Systems*, vol. 34, no. 3, pp. 2140-2151, May 2019, doi: 10.1109/TPWRS.2018.2886051.
[6] J. Zhao, X. Lyu, Y. Fu, X. Hu and F. Li, "Coordinated Microgrid Frequency Regulation Based on DFIG Variable Coefficient Using Virtual Inertia and Primary Frequency Control," in *IEEE Transactions on Energy Conversion*, vol. 31, no. 3, pp. 833-845, Sept. 2016, doi: 10.1109/TEC.2016.25375