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

CIGRE US National Committee
2021 Grid of the Future Symposium

Transient Stability Analysis Framework for Performance Evaluation of Microgrids with an Energy Storage System and a Synchronous Condenser

S. MOROVATI[1], F. KATIRAEI[2], S. CHUANGPISHIT[2]
The University of Tennessee[1], Quanta Technology[2]
USA

SUMMARY

Managing fault current level and dynamic performance during transient events are challenging aspects for design and operation of a microgrid that dominantly uses inverter-based resources (IBR). This paper discusses use of a Synchronous Condenser Machine (SCM) as a fault current source and to improve system dynamic responses for better voltage recovery. Although SCMs are not new in power system industry, their application in a microgrid and in conjunction with IBRs are not widely examined. The overall benefit of using SCM in a system reported in various research are outlined to be improving short circuit capacity, voltage regulation, and system inertia. This paper provides study results for comparative analysis of a microgrid operation with and without SCM for study cases defined in a transient stability analysis framework. The microgrid is dominantly using a battery energy storage system (BESS) to supply the load in an islanded scenario. The study shows that SCM can improve the microgrid stability and increase the fault current to the level expected from grid connected systems. However, supplementary control loops are essential for the microgrid to eliminate low-frequency oscillations – that are inherent to the operation of synchronous condenser as rotating machines in a weak system, and to provide active and reactive power balance in a microgrid in the presence of transient events.

KEYWORDS

Battery energy storage system, Inverter-based resources (IBR), Microgrids, Short circuit ratio (SCR), Synchronous Condenser, Transient stability, Voltage recovery.

smorovat@utk.edu

INTRODUCTION

High penetration of inverter-based resources (IBRs) in a microgrid raises many design challenges, although microgrids are recognized as superior solutions for reliability and power quality enhancement of distribution grids facing multiple outages and large voltage/frequency deviations. The low fault current level from power electronic inverters, which most of the time is very comparable to microgrid load adds the complexity of applying sophisticated protection schemes to ensure proper coordination in all operating conditions. The lack of inertia and limited reactive power may introduce slow voltage recovery response subsequent to faults or sudden load change events.

Unacceptable voltage and frequency excursions caused by deterioration of inertia response and system strength in the presence of significant disturbances, leading to instability are known as some of these challenges that can adversely impact the system reliability [1], [2]. To address the frequency stability challenges, distributed energy resource (DERs) in a microgrid, dominantly renewable energy resource based using power electronics, need to be equipped with frequency control methods to provide frequency regulation operations [3], [4]. The voltage instability is also a primary challenge in a microgrid with high penetration of DERs. However, reactive power compensation, defined as the reactive power management to improve the performance of power systems, can be considered as a effective solution by providing fast voltage recovery and reducing the magnitude and frequency of voltage fluctuations post fault [5], [6].

In recent years, the application of synchronous condensers is discussed as a potential solution for the future power system with high penetration of inverter-based renewable resources. A synchronous condenser is, in principle, a synchronous machine without the prime mover and has the advantages of improving short circuit strength, voltage regulation, and system inertia [7], [8], [9]. Furthermore, using a synchronous condenser for decreasing under-frequency load shedding is investigated in [10]. The interaction between active and reactive power channels of synchronous condensers to improve primary frequency regulation is also analysed and suggested in [11].

Due to the limited overload capability of semiconductors, replacing conventional power plants with inverter-based renewable energy resources can lead to a significant drop in the system short circuit strength, typically measured by the short circuit ratio (SCR) [12]. For a microgrid that uses IBR dominantly, SCR can be around 1.2 to 2, while for rotating machines, SCR is commonly above 5 or 6. By adding a SCM, the microgrid SCR can be adjusted to what is seen in grid connected systems. The significant enough difference in fault current level and load level will streamline the protection system design and coordination of protection equipment in a microgrid. However, SCM will bring added complexity of start-up process, controls, and additional spinning losses.

Comprehensive results from a microgrid simulation in the MATLAB Simulink platform are provided to investigate the system performance in the absence and presence of the SCM in the grid forming mode of operation (islanded system) where the SCM is running with an excitation system as a voltage regulatory service. The studies use a proposed transient stability analysis framework for BESS integrated microgrids. The primary goal of this framework is to introduce and incorporate realistic events that can lead to transient stability concerns for comparative analysis of a microgrid operation with/out SCM. The microgrid mainly uses an inverter-based BESS to supply the load in an islanded scenario. The study shows that SCM can improve the microgrid stability, voltage recovery and increase the fault current. However, it may need complex control loops for supplying the required reactive power in the microgrid and improve post-fault responses.

Transient Stability Analysis Framework for Microgrid

The transient stability analysis framework (TSAF) for a microgrid evaluates microgrid dynamic performance in response to several realistic scenarios that can commonly occur during a microgrid operation in an islanded mode, when isolated from the main grid. The major transient events considered are:

- Transition of a microgrid from a grid connected to an islanded mode under a large power mismatch (for instance, greater than 1/3 of microgrid size)
- Black start and load restoration in steps greater than 1/3 of microgrid size
- Step load increase that changes the power balance more than 1/3 of the microgrid size
- Load rejection (load drop about 1/3 of microgrid load), and
- Temporary faults internal to the microgrid (symmetrical or asymmetrical faults), which qualify for voltage and frequency ride-through requirements.

The detail of each transient event is further defined in the study section of the paper.

A simplified model of a utility-scale microgrid is used as a benchmark for transient analysis as shown in Fig. 1. The model simplification is considered by aggregating loads and defining load centres at 3 nodes across the microgrid. The microgrid operates at 12.47 kV, supplying about 3.5 MW of customer loads, using a 5 MW / 10 MWh BESS (main source) and some distributed PV systems (about 150kW). The short circuit capacities of the microgrid at node 1 and node 4 for the grid connected mode and islanded mode of operation with only BESS is given in Table 1.

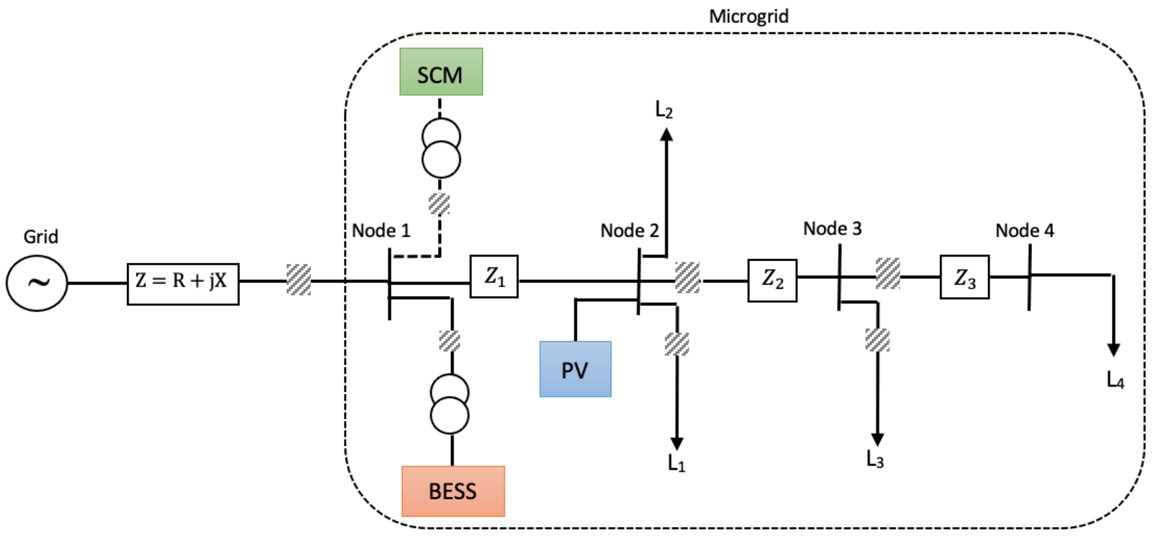

Fig. 1. Microgrid benchmark system (utility scale)

Table 1. Microgrid Strength

Fault current (kA)	Grid Connected Mode	Islanded Mode
Node 1	5.9	0.65
Node 4	1.5	0.55

Microgrid Operation with BESS Only

Comprehensive results of the microgrid operation with BESS only are illustrated in this section. The provided results capture: the output active and reactive power from the BESS, the RMS voltage and currents at the BESS point of connection, and the frequency deviation in the microgrid.

- Case 1A: Transition of a microgrid from a grid-connected to an islanded mode

In this case, the islanding happens at t=0.5 s by opening the breaker before node 1. The battery's reference active and reactive power in the grid-connected mode is set as 5 MW and 0, respectively. However, when the islanding happens, the active output power drops based on load size in the islanded microgrid. The RMS voltage, RMS current, and frequency deviations are shown in Fig. 2 (b), (c), and (d), respectively that can validate the stable transition from a grid-connected to the islanded mode.

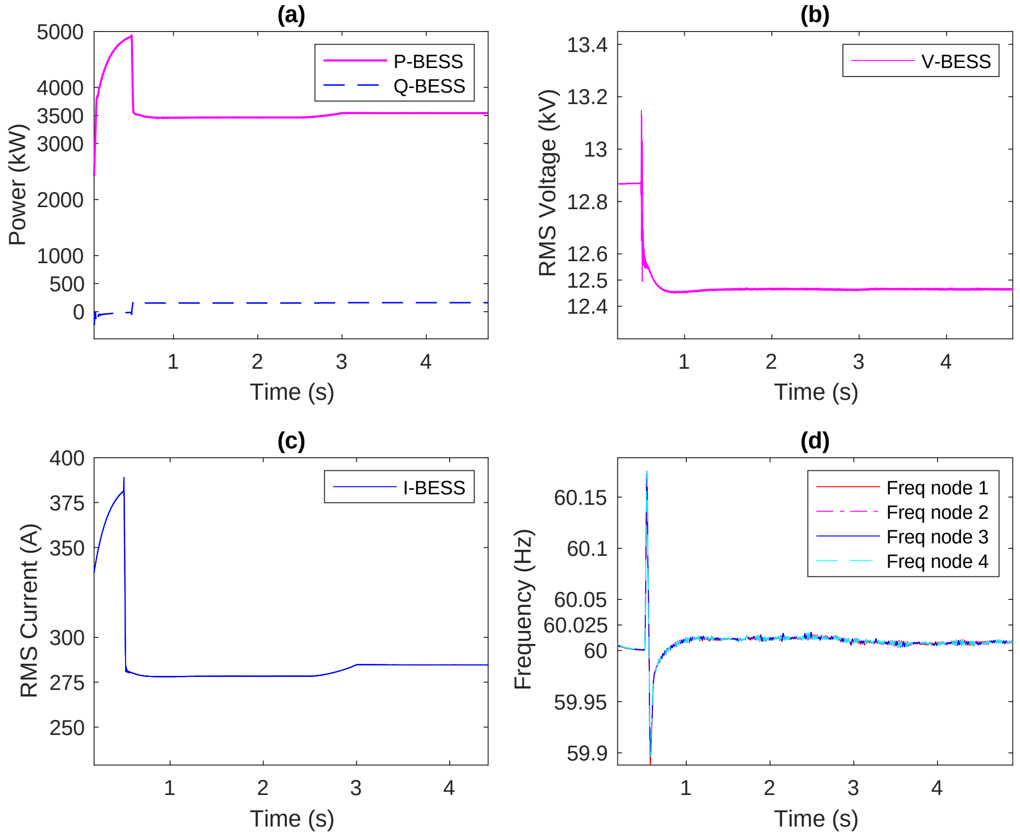

Fig. 2. BESS performance in transition of microgrid from a grid connected to an islanded mode. (a) Active and reactive power. (b) RMS voltage. (c) RMS current. (d) Frequency.

- Case 2A: Load rejection

As a second case, a 1 MW load rejection happens at t=7 s in the islanded microgrid at node 2. As illustrated in Fig. 3. (a), the BESS active power reduces based on the load drop in the microgrid, and the system becomes stable after a few seconds. The droop control can maintain the frequency deviation close to 60 Hz after applying disturbance, see Fig 3. (d).

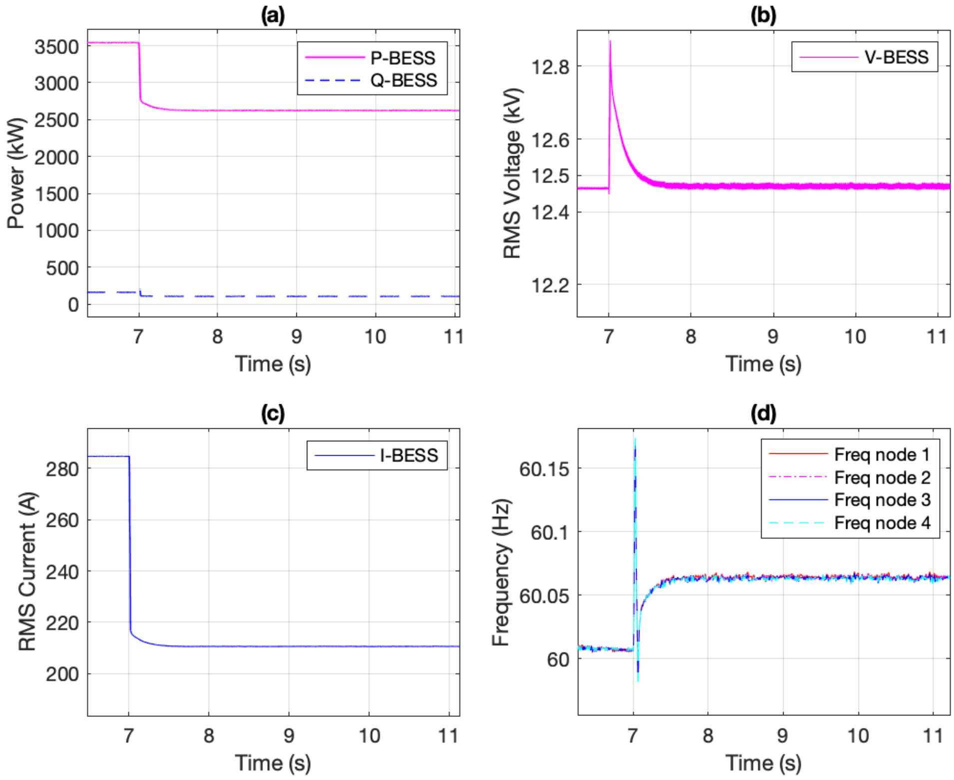

Fig. 3. BESS performance in load rejection. (a) Active and reactive power. (b) RMS voltage. (c) RMS current. (d) Frequency.

- Case 3A: Temporary symmetrical fault

In this case, a three-phase to ground fault is applied at t=7 s at node 3 and cleared after 9 cycles. The illustrated results in Fig. 5 show the BESS performance during the fault, where the observed short circuit current is about 650 A. The system performance is recovered after clearing the fault, as shown in BESS instantaneous voltage and frequency deviations in Fig. 5. (a) and Fig. 5 (b), respectively. Microgrid is stable; voltage and frequency are properly recovered. However, the key challenge would have been fault detection consider the closeness of fault current to the load current.

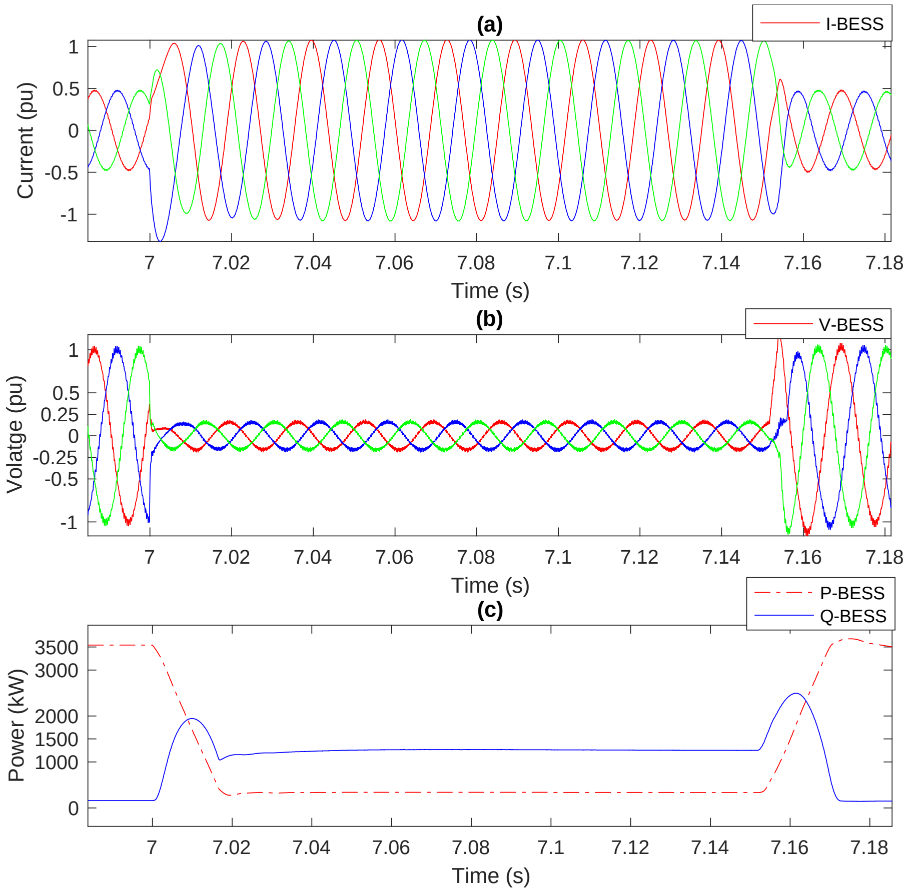

Fig. 4. BESS performance under three-phase fault. (a) Instantaneous voltage. (b) Instantaneous current(c) Active and reactive power.

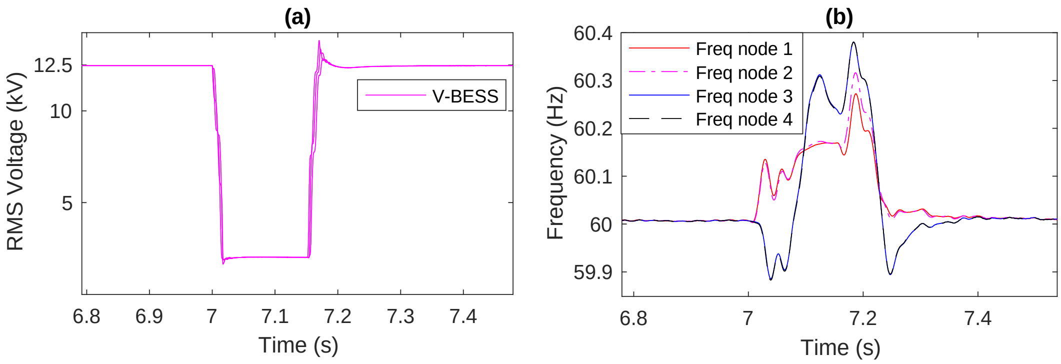

Fig. 5. BESS performance under three-phase fault. (a) RMS voltage. (b) Frequency.

- Case 4A: Temporary asymmetrical fault

This transient event is considered to analyze the voltage recovery performance under an asymmetrical fault (single phase to ground fault) applied at t=7 s, for 9 cycles at node 3. The voltage and currents are affected during the fault duration, and the recovery is made after clearing the fault at t=7.15 s. The active and reactive power of the BESS is shown in Fig. 6. (c), where Fig. 7. shows the RMS voltage and frequency deviation during the fault. The frequency regulation scheme can preserve the frequency deviations close to 60 Hz, and the recovery is made after clearing the fault. Note that the large fault current in this case is the transformer fault current that provides an effective grounding for the microgrid.

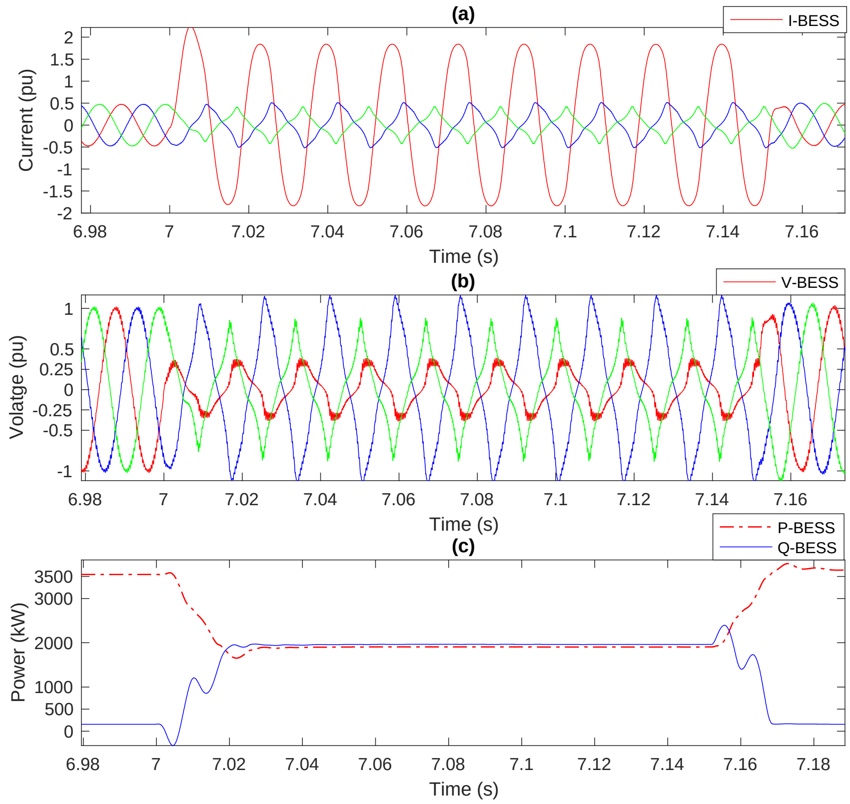

Fig. 6. BESS performance under single-phase fault applied at t=7 s at node 3. (a) BESS Current. (b) BESS voltage. (c) Active and reactive power

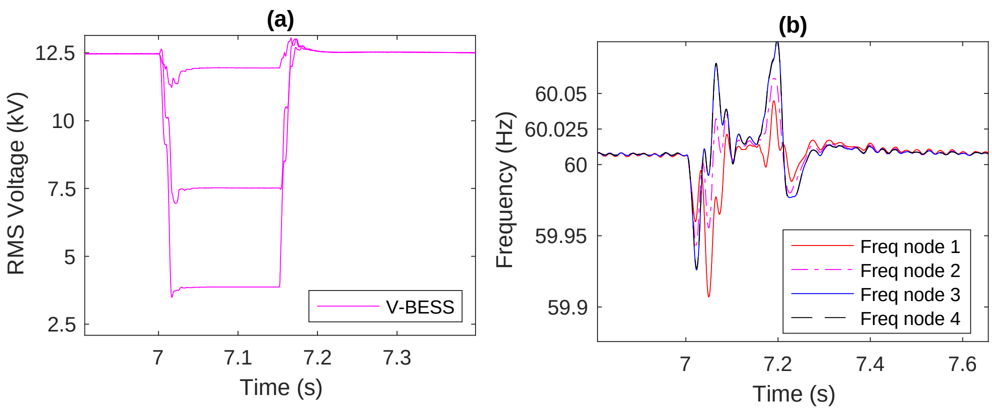

Figure 7. BESS performance (a) RMS voltage. (a) frequency deviations.

Microgrid Operation with BESS plus SCM

This section covers the study cases of the microgrid performance in the presence of SMC. Similar selected scenarios are illustrated to provide comparative results with case studies in the absence of SCM.

- Case 2B: Load rejection

In this case, similar to the BESS-only case study, a 1 MW load rejection happens at t=7 s in the islanded microgrid at node 2. As illustrated in Figure. 8. (a), the active power output reduces based on the load drop, and the system becomes stable again. The droop control can also preserve the frequency deviation close to 60 HZ after the load change (see Fig. 8. (d)). SCM active and reactive power, RMS voltage, and RMS current are presented in Fig. 9. It should be noted that SCM active and reactive power, although minor (in a few 100 kW/kvar range) appear as additional load for the microgrid, representing additional losses.

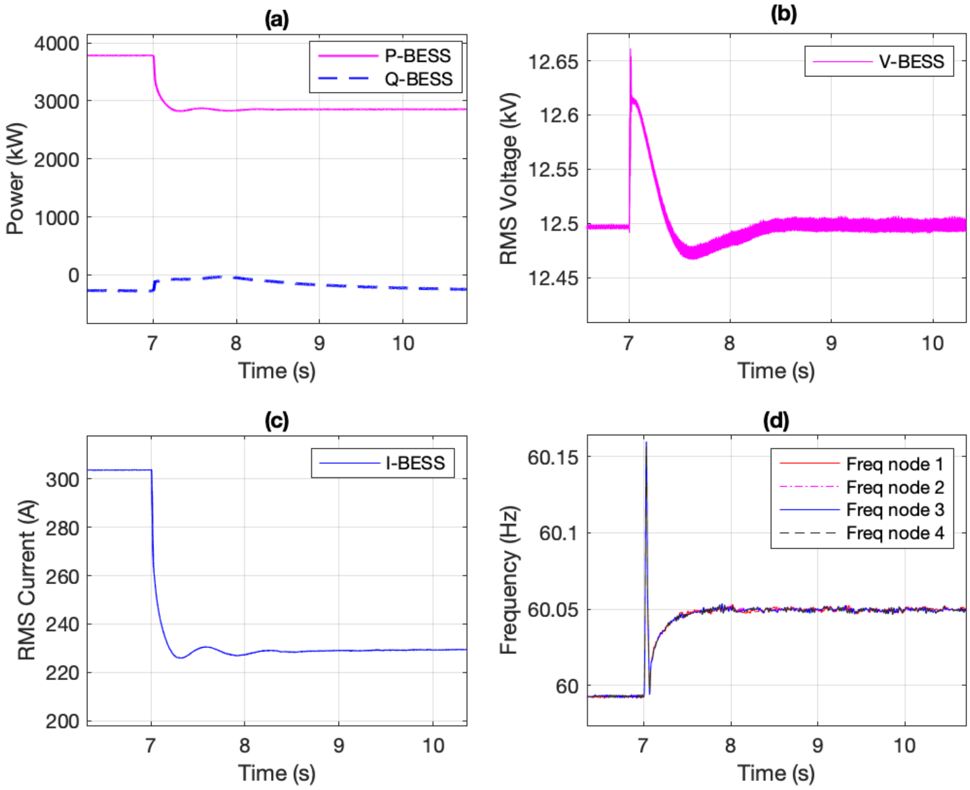

Fig. 8. BESS performance in the presence of SCM. (a) Active and reactive power. (b) RMS voltage. (c) RMS current. (d) Frequency.

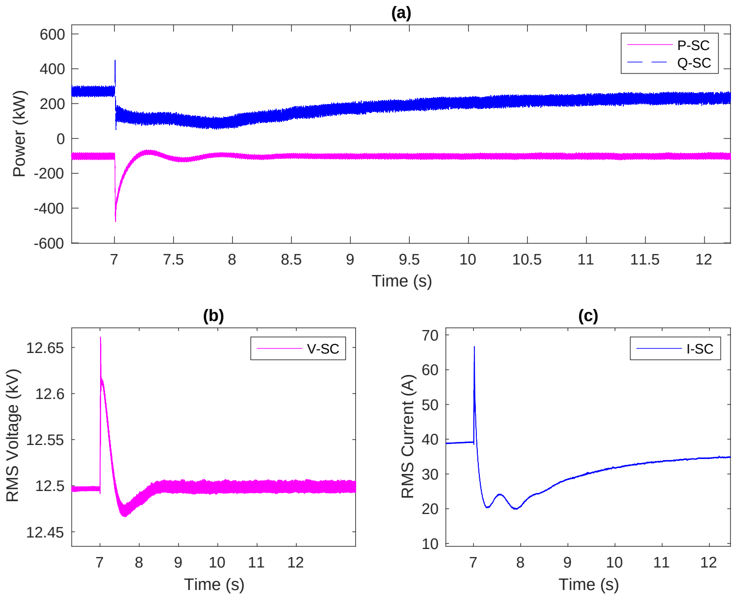

Fig. 9. SCM performance in load rejection. (a) Active and reactive power. (b) RMS voltage. (c) RMS current.

- Case 3B: Temporary symmetrical fault

This case investigates the voltage recovery in the islanded microgrid during and after applying a three-phase to ground fault for 9 cycles. As seen in Fig. 10. (b) voltage recovery is smoother in the presence of SCM with less drop during the fault. BESS RMS voltage and frequency deviation are presented in Fig. 11, which validate system stability after clearing the fault. SCM performance during the symmetrical fault at node 3 is shown in Fig. 12. Additional fault current contribution from SCM increases the total microgrid fault current above 2000A, representing an SCR of 5.

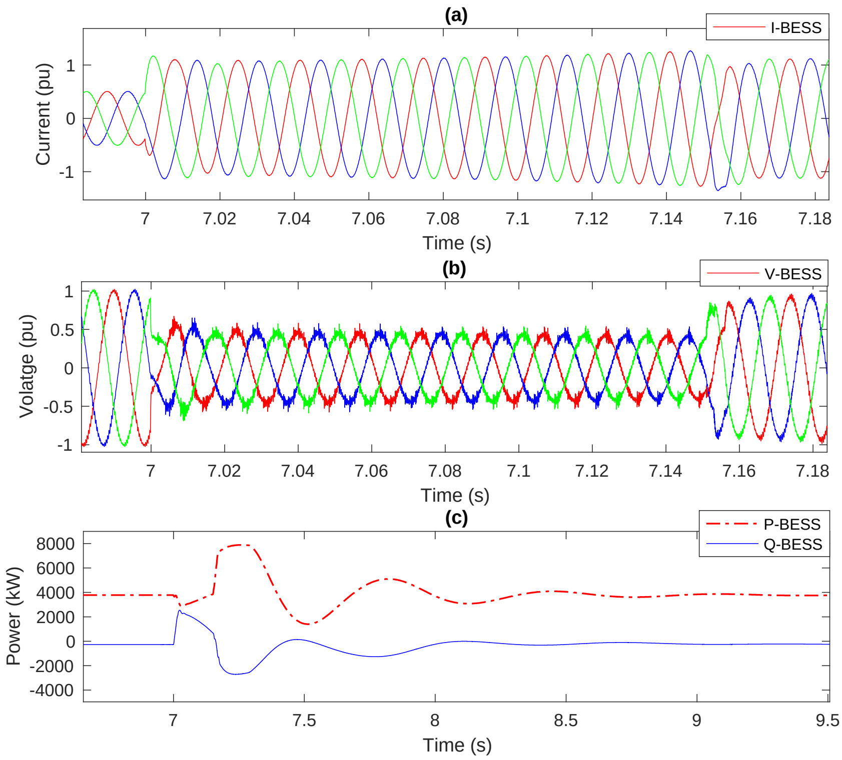

Fig. 10. BESS performance under three-phase fault in the presence of SCM. (a) BESS Current. (b) BESS voltage. (d) Active and reactive power.

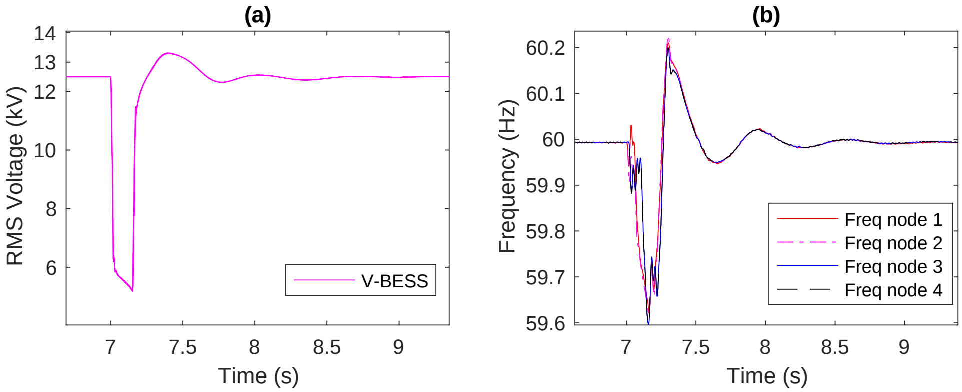

Fig. 11. BESS performance under three-phase fault in the presence of SCM. (a) RMS voltag. (b) Frequency.

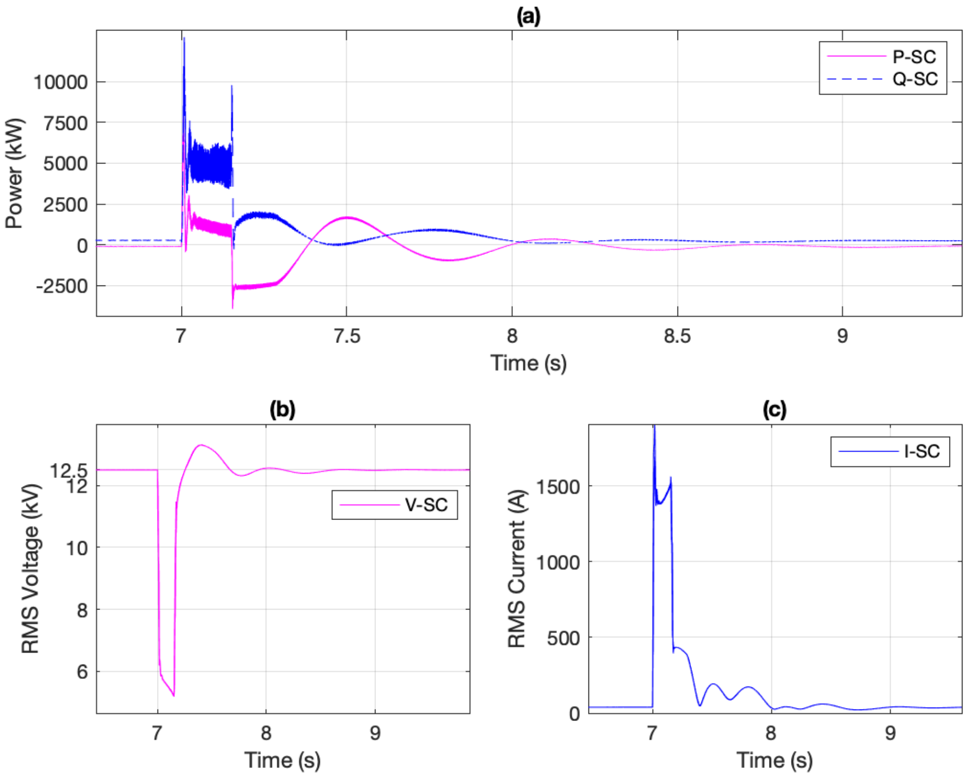

Fig. 12. SCM performance under a three-phase fault. (a) Active and reactive power. (b) RMS voltage. (c) RMS current.

- Case 4B: Temporary asymmetrical fault

In this case, a single-phase to ground fault is applied on the islanded microgrid at t=7 s for 9 cycles. Clearly, in the presence of SCM, the voltage recovery and current oscillations are smoother with less deviations, as shown in Fig. 13. Frequency changes in the microgrid and BESS RMS voltage are shown in Fig. 14. SCM performance helping the voltage recovery by injecting the reactive power to the microgrid is illustrated in Fig. 15.

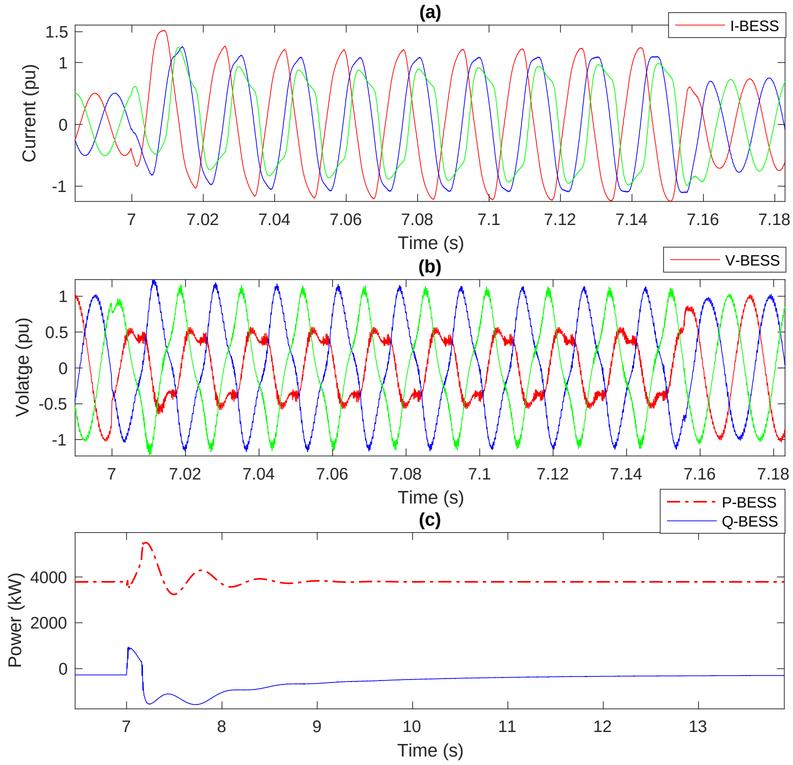

Fig. 13. BESS performance under single-phase fault in the presence of SCM. (a) BESS Current. (b) BESS voltage. (d) Active and reactive power.

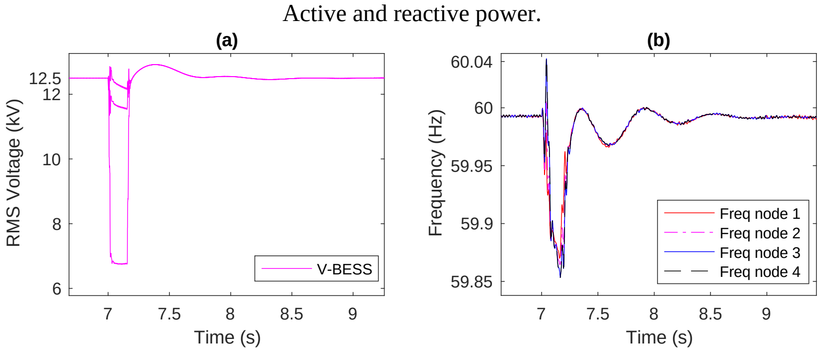

Fig. 14. BESS performance under single-phase fault in the presence of SCM. (a) RMS voltage. (b) Frequency.

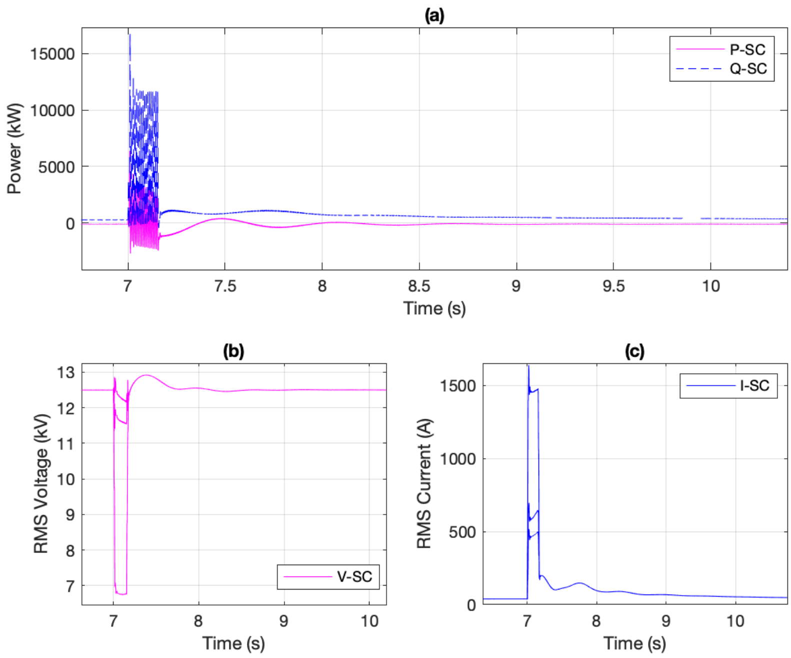

Fig 15. SCM performance under a single-phase fault. (a) Active and reactive power. (b) RMS voltage. (c) RMS current.

Comparative Analysis

The comparative analysis of microgrid response during a for evaluating the short circuit capacity of the islanded microgrid with and without SCM is provided in this section. In the presence of SCM, the voltage recovery is smoother with less deviation in the voltage magnitude during the fault. Fig. 16. shows the comparison of BESS voltage and current under a three-phase to ground fault applied at node 3 at t=7 s for 9 cycles in the presence and absence of SCM. Similar comparison for the BESS performance under a single phase to ground fault is illustrated in Fig. 17. The level of microgrid fault current for both BESS only and BESS with SCM under a three-phase fault (TPH) and single-phase fault (SLG) is presented in Table 2. The symmetrical fault current contribution has significantly improved, which facilitate proper protection system design and device to device coordination for achieving selectiveness in fault clearing areas to improve reliability and dependability on conventional protection schemes.

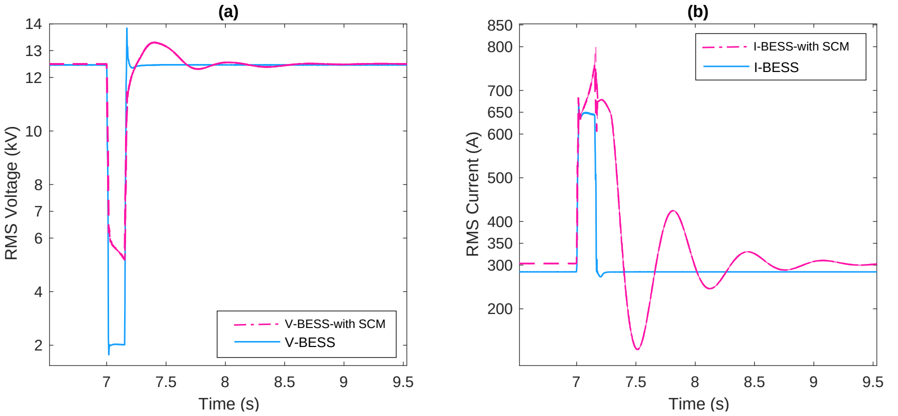

Fig. 16. BESS performance under a three-phase fault in the presence and absence of SCM

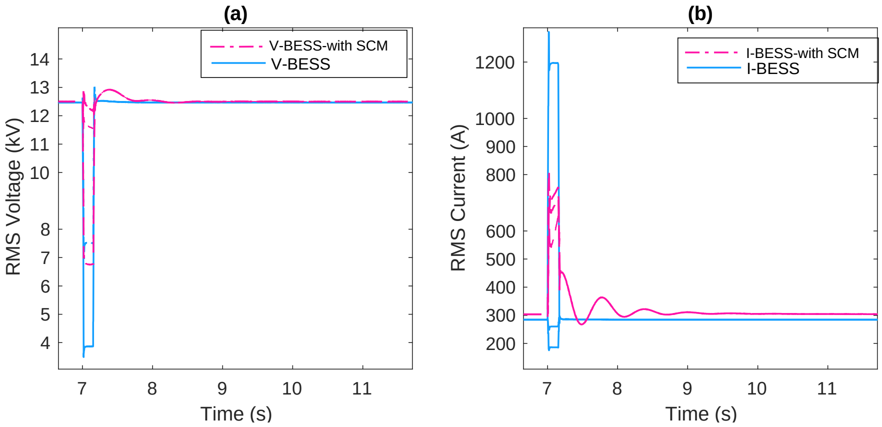

Fig. 17. BESS performance under a single-phase fault in the presence and absence of SCM

Table 2. Level of Fault Current

Fault type	BESS only	BESS + SCM
TPH	650 A	1875 A
SLG	1200 A	744 A

Conclusions

In this paper, the TSAF for a microgrid is studied for microgrid transient performance evaluation in the presence and absence of SCM in an islanded microgrid. Comprehensive results for comparative analysis of a microgrid operation with/out SCM for selected study cases, including load rejection, symmetrical and asymmetrical faults are proposed to evaluate the microgrid transient stability and performance. The study shows that SCM can improve the microgrid stability, increase the three-phase fault current level, and smooth the voltage recovery when compared with cases without SCM. However, optimal usage of SCM may need other additional control loops for active and reactive power control to provide the required reactive power to the microgrid. Moreover, the study results show that a supplementary frequency control loop is needed to provide accurate synthetic inertia in an islanded microgrid to provide guaranteed frequency regulation post disturbances such as load rejection.

BIBLIOGRAPHY

[1] Morovati, Samaneh, Yichen Zhang, Seddik M. Djouadi, Kevin Tomsovic, Andrew Wintenberg, and Mohammed Olama. "Robust Output Feedback Control Design for Inertia Emulation by Wind Turbine Generators." IEEE Transactions on Power Systems (2021).

[2] S. Wang and K. Tomsovic, “A novel active power control framework for wind turbine generators to improve frequency response,” *IEEE Trans. Power Syst.*, vol. 33, no. 6, pp. 6579–6589, 2018.

[3] M. Dreidy, H. Mokhlis, and S. Mekhilef, “Inertia response and frequency control techniques for renewable energy sources: A review,” Renewable and Sustainable Energy Reviews, vol. 69, pp. 144–155, 2017.

[4] Morovati, Samaneh, and Héctor Pulgar-Painemal. "Control coordination between DFIG-based wind turbines and synchronous generators for optimal primary frequency response." In 2020 52nd North American Power Symposium (NAPS), pp. 1-6. IEEE, 2021.

[5] T. J. E. Miller, Reactive Power Control in Electric Power Systems. New York: Wiley, 1982.

[6] Teleke, Sercan, Tarik Abdulahovic, Torbjörn Thiringer, and Jan Svensson. "Dynamic performance comparison of synchronous condenser and SVC." IEEE Transactions on Power Delivery, 23, no. 3 (2008): 1606-1612.

[7] Jia, Jundi, Guangya Yang, Arne Hejde Nielsen, Eduard Muljadi, Peter Weinreich-Jensen, and Vahan Gevorgian. "Synchronous condenser allocation for improving system short circuit ratio." In 2018 5th International Conference on Electric Power and Energy Conversion Systems (EPECS), pp. 1-5. IEEE, 2018.

[8] M. Nedd, Q. Hong, K. Bell, C. Booth, and P. Mohapatra, “Application of synchronous compensators in the gb transmission network to address protection challenges from increasing renewable generation,” in Proc. Cigre Study Committee B5 Colloquium, Auckland, New Zealand, Sep. 2016, pp. 1–6.

[9] S. Kynev, G. Pilz, and H. Schmitt, “Comparison of modern statcom and synchronous condenser for power transmission systems,” in Proc. IEEE Electrical Power and Energy Conference, Ottawa, Canada, Oct. 2016, pp. 1–6

[10] Y. Katsuya, Y. Mitani, and K. Tsuji, “Power system stabilization by synchronous condenser with fast excitation control,” in Proceedings of 2000 International Conference on Power System Technology, Perth, Australia, Dec. 2000, pp. 1563-1568.

[11] H. T. Nguyen, G. Yang, A. H. Nielsen et al., “Hardware and software- in-the-loop simulation for parameterizing the model and control of syn- chronous condensers,” IEEE Transactions on Sustainable Energy, vol. 10, no. 3, pp. 1593-1602, Jul. 2019.

[12] Kenyon, Rick Wallace, Anderson Hoke, Jin Tan, and Bri-Mathias Hodge. "Grid-Following Inverters and Synchronous Condensers: A Grid-Forming Pair?" In 2020 Clemson University Power Systems Conference (PSC), pp. 1-7. IEEE, 2020.

[13] Li, Hao, Honghua Wang, Hangtian Lu, and Chengliang Wang. "Design of LQR Excitation Controller of Synchronous Condenser in HVDC System." In Journal of Physics: Conference Series, vol. 1884, no. 1, p. 012004. IOP Publishing, 2021.

[14] Wang, Puyu, Qingwen Mou, Xing Liu, Wei Gu, and Xuan Chen. "Start-up control of a synchronous condenser integrated HVDC system with power electronics based static frequency converter." IEEE Access 7 (2019): 146914-146921.

[15] Giroux, Pierre & Tremblay, Olivier & Sybille, Gilbert & Brunelle, Patrice. (2021). Microgrid Dynamic Operation Example. 10.13140/RG.2.2.13887.64162.