Journal of the Korea Academia-Industrial cooperation Society
Vol. 22, No. 7 pp. 1-10, 2021

https://doi.org/10.5762/KAIS.2021.22.7.1
ISSN 1975-4701 / eISSN 2288-4688

Transient Operation Characteristics of 30kW Scale CVCF Inverter-based Micro-grid System

Marito Ferreira, Hu-Dong Lee, Jian Shen and Dae-Seok Rho*
Dept. of Electrical Engineering, Korea University of Technology and Education

30kW급 CVCF 인버터 기반 마이크로그리드 시스템의 과도상태 운용특성에 관한 연구

페레이라 마리토, 이후동, 신건, 노대석*
한국기술교육대학교 전기공학과

Abstract For the purpose of reducing carbon dioxide (CO_2) emissions in island areas, countermeasures are being studied to operate off-grid micro-grid (MG) systems in a stable manner by increasing the proportion of renewable energy sources (RES) instead of diesel generators (DG). However, in the operation of a constant-voltage and constant-frequency (CVCF) inverter-based MG system, a phenomenon of energy sinking can occur when the output of renewable energy sources (RES) is greater than customer loads in the off-grid MG system. The voltage of the battery system in the CVCF inverter of the MG system can rapidly increase depending on the state of charge (SOC), and then blackout in the entire MG system might occur due to the shut-down of the CVCF inverter. Therefore, in order to overcome these problems, this paper deals with a transient operation strategy for a CVCF inverter-based MG system to prevent the shut-down of the CVCF inverter despite the energy sinking phenomenon. Based on the transient operation strategy, we implemented a test device for a 30-kW CVCF inverter-based MG system in order to find out the transient operation characteristics related to energy sinking in the CVCF inverter. From test results based on a transient operation strategy, it was confirmed that the shut-down of the CVCF inverter can be prevented according to the SOC and voltage of the battery system in a CVCF inverter.

요 약 이산화탄소 배출의 저감을 위하여 도서지역의 신재생에너지전원 및 ESS의 도입이 확대되면서, 디젤발전기 대신 CVCF 인버터가 주 전원인 Micro-grid(MG) 시스템을 안정적으로 운용하는 방안들이 연구되고 있다. 그러나, CVCF 인버터 기반의 MG 시스템에서는 전체 부하보다 신재생에너지전원의 출력이 큰 경우에 에너지 Sinking(과도상태) 현상이 발생하게 된다. 이 때, CVCF 인버터용 배터리의 SOC 상태에 따라, 배터리 전압이 급격히 상승하여, 인버터의 과전압 보호동작에 의해 CVCF 인버터가 탈락되어 MG 전체 계통에 정전을 유발할 수 있다. 따라서, 본 논문에서는 CVCF 인버터를 기반으로 한 도서지역용 MG 시스템의 안정적인 운용을 위하여, 에너지 Sinking이 발생한 경우의 운용특성을 분석하고, CVCF 인버터가 에너지 Sinking 시에 탈락되는 것을 사전에 방지할 수 있는 MG 시스템의 과도상태 운용전략을 제안한다. 또한, CVCF 인버터, 태양광전원, 수용가부하로 구성된 30kW급 MG 시스템 시험장치를 구현하여, 실 계통에서의 에너지 Sinking에 의한 CVCF 인버터 기반 MG 시스템의 과도상태 시 운용특성을 제시한다. 한편, 30kW급 시험장치와 제안한 운용전략을 바탕으로 MG 시스템의 과도상태 운용특성을 분석한 결과, CVCF 인버터용 배터리의 전압과 SOC에 따라 인버터가 탈락하는 과도상태를 사전에 방지할 수 있어, 본 논문의 유용성을 확인하였다.

Keywords : Carbon-Free Off-Grid Micro-Grid System, CVCF Inverter, Battery System, Energy Sinking, Transient Operation Strategy, 30kW Scale Test Device

---

본 논문은 산업통상자원부의 재원으로 한국에너지기술평가원의 연구(No.20206910100090)와 한국에너지기술평가원의 연구(No.20191210301940)에 의하여 수행되었음.
*Corresponding Author : Dae-Seok Rho(Korea University of Technology and Education)
email: dsrho@koreatech.ac.kr
Received April 1, 2021 Revised April 30, 2021
Accepted July 2, 2021 Published July 31, 2021

1. Introduction

Recently, global warming, fine dust, and air pollution issues have been emerging as worldwide concerns. To overcome the energy and environmental challenges, the expansion of RES has been widely performed and the carbon-free off-grid MG system has been actively installed as one of the alternatives[1,2]. In other words, the countermeasures to increase the proportion of RES operation instead of diesel generator are being energetically studied. Particularly, in the carbon-free off-grid MG system, CVCF inverter is introduced to replace diesel generators for controlling the system voltage and frequency in MG system[3,4]. However, CVCF inverter-based MG system has a possibility of an energy sinking phenomenon when the output of RES is greater than customer loads in MG system. During the phenomenon, voltage of the battery system in CVCF inverter can rapidly increase depending on the SOC condition of battery system, and then blackout in MG system might be occurred due to shut-down of CVCF inverter.

Therefore, this paper presents the transient operation strategy for a stable operation of CVCF inverter-based MG system to prevent the shut-down of the CVCF inverter despite the energy sinking phenomenon in advance. And also, this paper implements a test device for 30kW CVCF inverter-based MG system, which is composed of CVCF inverter, artificial PV system, and artificial customer load. And then present operation characteristics of CVCF inverter-based MG system in 3-cases of operation stage including normal, transient, and restoration operation stage. From test results based on transient operation strategy, it is confirmed that the shut-down of CVCF inverter can be prevented in advance according to operation conditions of SOC and voltage of the battery system in a CVCF inverter.

2. Operation characteristics of CVCF inverter-based MG system

The off-grid MG system is generally composed of a diesel generator, RES, ESS, and customer loads which are illustrated in Fig. 1. Here, diesel generator and RES are supplying power to customer load, while ESS performs various operation functions such as load control and output stabilization of RES.

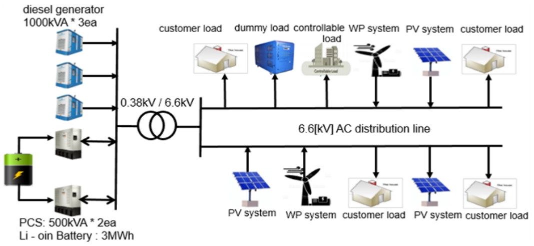


Fig. 1. General configuration of off-grid MG system

On the other hand, for the purpose of reducing carbon dioxide(CO_2) emissions in the island areas with an increase of operation in RES, a CVCF inverter-based MG system replacing diesel generator, as shown in Fig. 2, is being demonstrated and its stable operation methods are also being required[5,6].

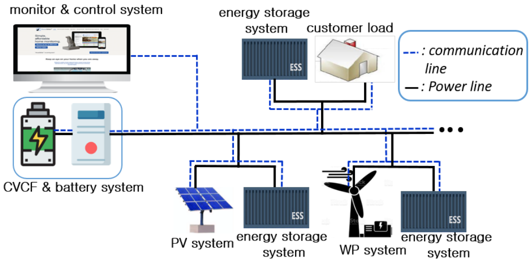


Fig. 2. Configuration of CVCF inverter-based MG system

3. Transient operation characteristics of CVCF inverter-based MG system

3.1 Concept of transient operation in CVCF inverter-based MG system

The phenomenon of energy sinking can be occurred unintentionally in a CVCF inverter when the total output of RES is greater than the total customer load in the CVCF inverter-based MG system. Fig. 3 shows a detailed mechanism of energy sinking in a single-phase half-bridge inverter. As shown in Fig. 3, while the inverter is being operated with the constant voltage and constant frequency by the control signal from a PWM controller, the surplus energy of RES may flow into a DC side of the inverter through a semi-conductor switch and the freewheeling diode[7]. However, the rectified voltage through a Q1 diode in Fig. 3 is not generally higher than voltage of DC side, the surplus energy cannot flow into a DC side.

When a Q2 is switch-on, the surplus energy flows from the AC to DC side of an inverter due to the voltage boosting at an inductor (L) of the AC side. Furthermore, during the process of the surplus energy flow, voltage rising of RES in AC side may be accelerated to supply power to MG system depending on SOC condition of battery system in CVCF inverter and then PWM controller in CVCF is performed in order to reduce a pulse width.

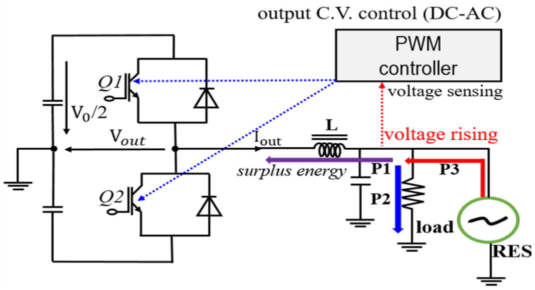


Fig. 3. Concept of energy sinking mechanism in half-bridge single phase inverter

Therefore, during the phenomenon of energy sinking, the battery system in CVCF inverter can be charged in an unintentional manner, and the voltage of the battery system can rapidly increase depending on the SOC condition, and then blackout in a MG system might be occurred due to over voltage protection operation of the CVCF inverter, as shown in Fig. 4.

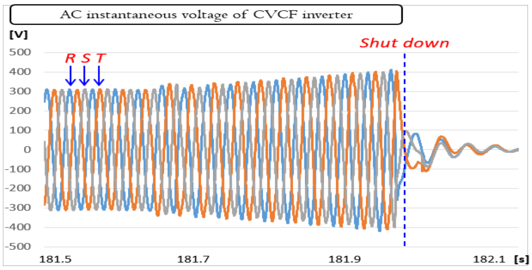


Fig. 4. Shut-down of CVCF inverter in case of energy sinking

Meanwhile, Fig. 5 shows the relationships between SOC and voltage of the lithium-ion battery system, and a terminal voltage of the battery system can dramatically increase at a C-V charging, which is more than 85% of SOC[8]. Namely, during the phenomenon of energy sinking, if the SOC is lower than 85%, the voltage at the DC side of CVCF inverter may not fluctuate significantly with C-C charging characteristics, however, if the SOC is higher than 85%, the voltage at DC side of the inverter can rapidly increase with C-V charging characteristics, and then shut-down in the inverter is occurred due to over voltage protection operation.

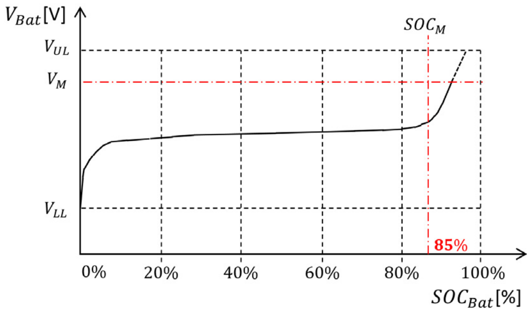


Fig. 5. Transient operation characteristics of CVCF inverter-based MG system

3.2 Transient operation strategy in CVCF inverter-based MG system

In order to prevent the shut-down of CVCF inverter despite the energy sinking phenomenon in advance, this paper deals with a transient operation strategy of the MG system for controlling PV system and CVCF inverter. In other words, while the CVCF inverter tolerates a certain amount of energy sinking, PV systems should be curtailed step by step before the voltage of the battery system violates the allowable range to maintain the MG system in a stable operation mode, as shown in Fig. 6.

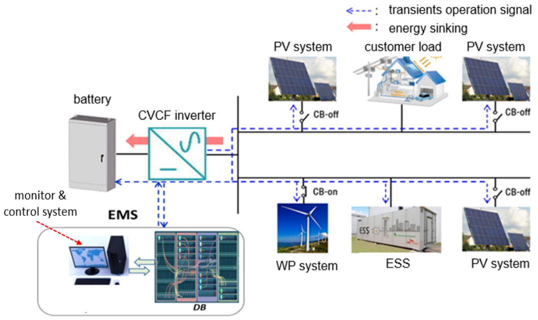
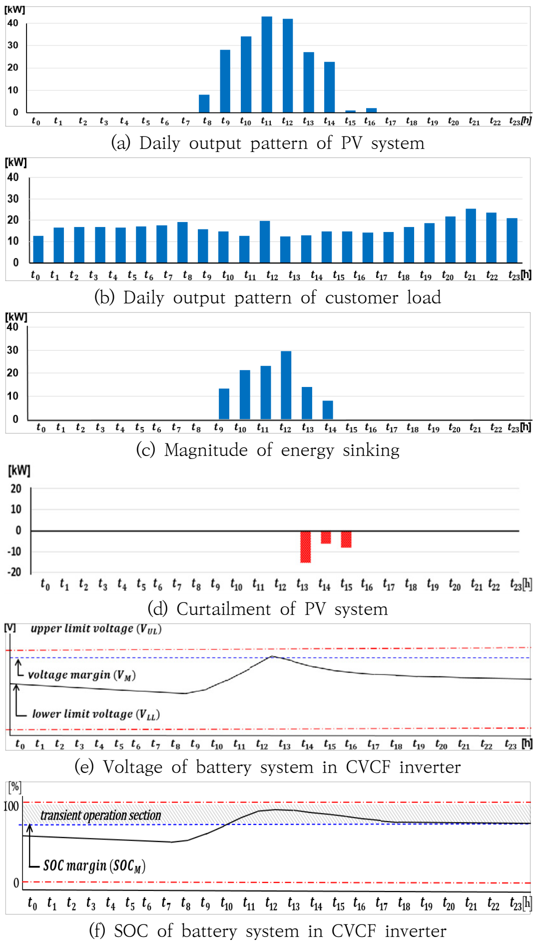


Fig. 6. Concept of transient operation strategy in CVCF inverter-based MG system

Meanwhile, the detailed operation strategy of transient state in off-grid MG system is demonstrated in Fig. 7. Where, the output of PV system and the daily patterns of customer load are indicated in Fig. 7 (a) and (b), and Fig. 7 (c) shows the magnitude of energy sinking which can be occurred when the capacity of PV system is greater than the customer load. And also, Fig. 7 (d) and (e) represent the characteristics of SOC and voltage of the battery system in CVCF inverter. During high solar radiation period which is from t_9 to t_{14} in Fig. 7 (b), SOC and voltage of the battery system in CVCF inverter-based MG system is rapidly increased with proportion to the magnitude of energy sinking. When the voltage of battery system violates the operation range($V_{LL}\sim V_{UL}$), the MG system can be immediately shut-down due to the over voltage protection of CVCF inverter based-MG system as well as BMS for battery system.

To prevent an unexpected shut-down of the inverter, the MG system operator can take measures to reduce the output of the interconnected PV system or to increase the charging capacity of ESS during the transient state t_{13} to t_{15}, as shown in Fig. 7 (d). As the magnitude of energy sinking is decreased, and the voltage of battery system and SOC is reduced during t_{13} to t_{15} period in Fig. 7 (e) and (f), the MG system returns to normal operation.



(a) Daily output pattern of PV system

(b) Daily output pattern of customer load

(c) Magnitude of energy sinking

(d) Curtailment of PV system

(e) Voltage of battery system in CVCF inverter

(f) SOC of battery system in CVCF inverter

Fig. 7. Transient operation strategy of CVCF inverter-based MG system

4. Implementation of test device for 30kW CVCF inverter-based MG system

4.1 CVCF inverter

The hardware system of CVCF inverter is designed and implemented to receive power from a DC battery and converted it into AC power through an insulated gate bipolar transistor(IGBT) component. And also, it adapts a pulse width modulation(PWM) control method with the capacity of 30kW, and the efficiency is more than 90%. Furthermore, it plays an important role to maintain a constant voltage and constant frequency in the MG system. Table 1 shows the detailed specifications of 30kW CVCF inverter.

Table 1. Specification of CVCF inverter

items	specification standards	
inverter	control element	frequency switching microprocessor with PWM methods
	type	IGBT
output	connection type	3ϕ4-wire with grounding
	rated voltage	380V
	power factor	0.8
	voltage distortion	within 5%
	voltage stability	within ± 1%
	transient voltage fluctuation	within ± 5%(100% of sudden load changing)
	speed of transient response	within 50msec
	frequency stability	within 60Hz ± 0.1Hz
	voltage regulation range	within ± 10%

On the other hand, in order to protect the battery system from any fault or transient state, the configuration of battery system including the battery management system(BMS) can be cut off undesirable issues such as under voltage, over voltage, and over current, and so on, as shown in Fig. 8.

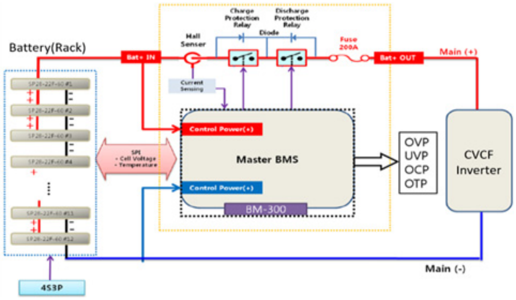


Fig. 8. Configuration of battery system in CVCF inverter and BMS

4.2 Artificial PV system

In order to design the output of an artificial PV system same as a real distribution system, this paper implements the artificial PV system, which is composed of 20[kVA] 3-phase inverter and 20[kW] DC power supply is illustrated in Fig. 9. And also, the output voltage of the artificial PV system can be adjusted by varying the DC currents.

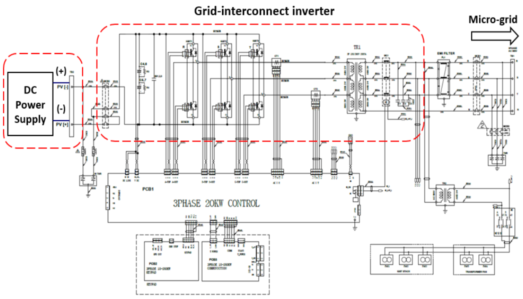


Fig. 9. Configuration of artificial PV system

4.3 Artificial customer load

The artificial customer load, which is composed of resistance(R) and reactance(X) component is implemented as shown in Fig. 10. Where the capacity of resistance(R) component is adjusted from 0.1[Ω] to 1.6[Ω], by 0.1[Ω], and the reactance(X) component is designed same as the resistance component.

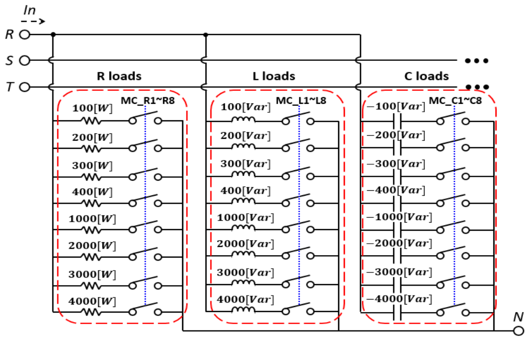


Fig. 10. Configuration of artificial customer load

4.4 Entire system

Based on the test devices as mentioned earlier, the entire configuration of 30kW scale CVCF inverter -based MG system, which is composed of 30kW CVCF inverter, 20[kW] artificial PV system, and 30[kW] artificial customer load, in order to maintain a constant voltage and constant frequency in the MG system is illustrated in Fig. 11.

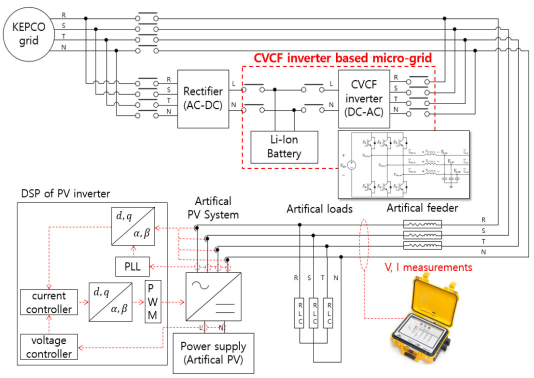


Fig. 11. Configuration of entire system

5. Case studies

5.1 Test conditions

In order to confirm the usefulness of the strategy for the transient operation in a CVCF inverter-based MG system, this paper assumes the configuration of 30kW CVCF inverter-based MG system, which is composed of the battery system in CVCF inverter, distribution feeder and customer load, and PV system, as shown in Fig. 12, and also assumes the operation conditions and setting values for each component in Table 2. Where, the arrow directions in Fig. 12 shows an energy sinking phenomenon of transient operation, which is occurred unintentionally in a CVCF inverter when the capacity of RES is greater than the total customer load in the CVCF inverter-based MG system, and also the condition of energy sinking is to increase the output of PV system from 0[kW] to 18[kW] by 3[kW] unit when the capacity of customer load is fixed as 6[kW].

Furthermore, the operation limit of SOC setting value of the battery system in the CVCF inverter in Table 2 is assumed as 85% and the operation limit voltage is determined as 131.8[V] by considering an operation margin of 95% of the maximum voltage of the CVCF inverter. On the other hand, the scenarios of transient operation in the CVCF inverter-based MG system are classified into 3 cases. Here, Case I is a normal operation mode where the SOC of battery system in CVCF inverter is maintained as less than 85%, Case II is a transient operation mode where the SOC is more than 85%, and case III is the restoration operation mode to cut off the renewable energy source step by step. And also, the initial value of SOC in Case I is assumed as 50%, and the SOC in Case II and Case III are as 90%.

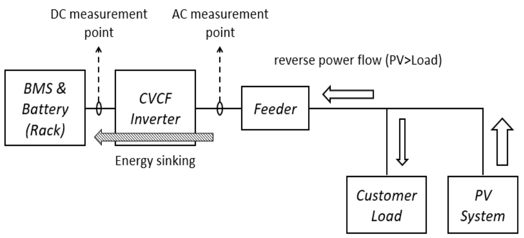


Fig. 12. Configuration of 30kW CVCF inverter-based MG system

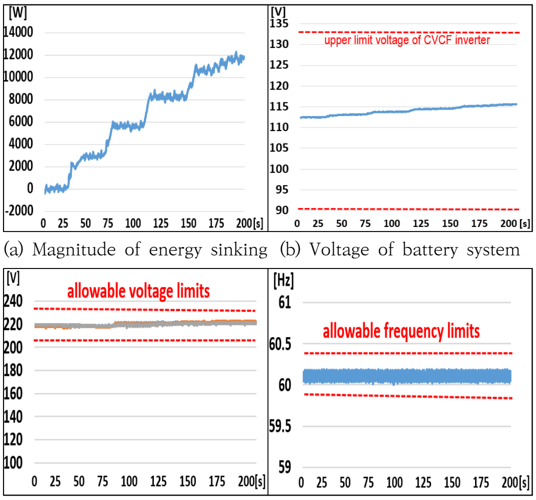
Table 2. Test conditions

items	conditions	
battery (rack)	configuration of cell	32S84P (Lithium-ion cell, 3.7V)
	voltage operation range of (BMS)	89.6 ~ 134.4[V]
CVCF inverter	setting of SOC(SOC_M)	85[%]
	range of operation voltage(DC input)	90 ~ 134[V]
	AC output voltage & frequency	220 ± 6% [V] & 60 ± 0.2 [Hz]
	setting of voltage(V_M)	131.8[V] (η=0.95)
	customer load	6[kW]
	PV system	0 ~ 18[kW]

5.2 Transient operation characteristics of CVCF inverter based MG system using test device

5.2.1 Characteristics of normal operation mode (Case I)

This paper implements a test device for 30kW CVCF inverter-based MG system in order to evaluate normal operation characteristics CVCF inverter-based MG system when the SOC of battery system is 50%, as shown in Fig. 13. Where, Fig. 13 (a) show magnitudes of energy sinking at time interval and Fig. 13 (b) is the voltage of the battery system in CVCF inverter along with the magnitude of energy sinking, and also, Fig. 13 (c) and (d) are the operation voltage and frequency of MG system. As shown in Fig. 13, when the magnitude of energy sinking increases from 0[kW] to 12[kW] by 3[kW] unit at each time interval, it is found that voltage of the battery system can significantly increase from 112.5[V] to 115.7[V]. However, since the voltage of battery system does not violate the operating voltage range of an inverter, it is confirmed that the operation voltage and frequency of MG system can be maintained in a stable manner.



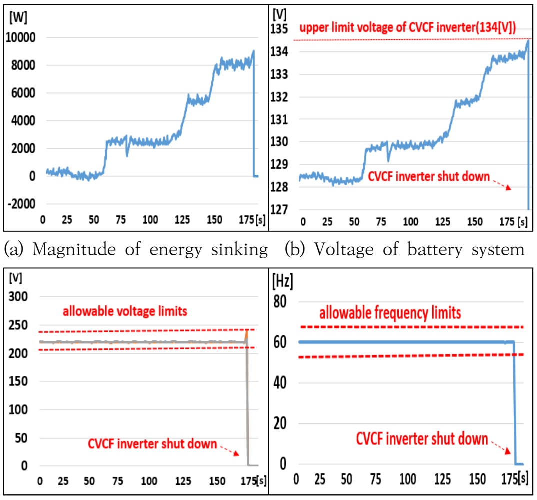
(a) Magnitude of energy sinking (b) Voltage of battery system

(c) Voltage of MG system (d) Frequency of MG system

Fig. 13. Characteristics of normal operation mode (Case I)

5.2.2 Characteristics of transient operation mode (Case II)

When SOC of the battery system in CVCF inverter is 90%, which includes transient operation range, the characteristics of CVCF inverter-based MG system is illustrated in Fig. 14. Here, when the energy sinking occurs at 90% SOC of battery system with the lack of operation margin, it is confirmed that voltage of CVCF inverter can



(a) Magnitude of energy sinking (b) Voltage of battery system

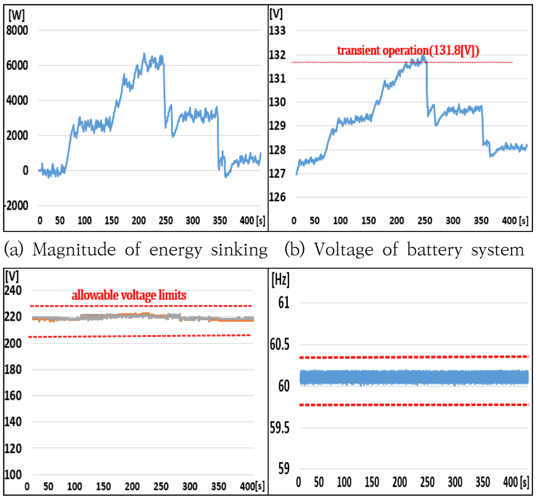
(c) Voltage of MG system (d) Frequency MG system

Fig. 14. Characteristics of transient operation mode (Case II)

rapidly increase from 128.2[V] to 134.3[V], and then the inverter may result in shutting down due to the violation of the allowable voltage limit of 90~134[V]. Therefore, when the SOC of battery system is operated within the transient operation range as shown in Fig. 14, it is clear that the proper solution for the energy sinking is being required.

5.2.3 Characteristics of transient restoration mode(Case III)

In order to overcome the problems in Case II, the operation characteristics of CVCF inverter-based MG system with the operation strategy are illustrated in Fig. 15. Here, when more than 6[kW] of the energy sinking occurs at 90% SOC of battery system, voltages of the battery system in CVCF inverter can reach 131.8[V] starting from 128.5[V], which is the setting value of 95% allowable maximum voltage limit of 134[V]. At the same time when voltage of the battery system reaches the setting value, PV systems are starting to cut off 3[kW] units step by step according to the operation strategy in order to restore the normal operation stage. From the restoration procedures, it is clear that the magnitudes of energy sinking and voltage of the battery system are being simultaneously reduced and maintained within the proper operation range.



(a) Magnitude of energy sinking (b) Voltage of battery system

(c) Voltage MG system (d) Frequency of MG system

Fig. 15. Characteristics of restoration operation mode(Case III)

6. Conclusions

This paper has presented the transient operation strategy for a stable operation of CVCF inverter-based MG system to prevent the shut-down of CVCF inverter despite the energy sinking phenomenon in advance. And also, implements a test device for 30kW CVCF inverter-based MG system in order to find out transient operation characteristics related to energy sinking in a CVCF inverter. The main results are summarized as follows.

(1) In case of normal operation(Case I), it is found that voltage of the battery system can significantly increase from 112.5[V] to 115.7[V]. However, it is confirmed that the operation voltage and frequency of MG system can be maintained in a stable manner due to plenty of margin in SOC of the battery system because the voltage of battery system does not violate the operation voltage range of an inverter.

(2) In case of transient operation(Case II), it is confirmed that voltage of CVCF inverter can rapidly increase from 128.2[V] to 134.3[V], and then the inverter may result in shutting down due to the violation of the allowable voltage limit of 90 to134[V].

(3) In the case of restoration operation(Case III), it is clear that the magnitudes of energy sinking and voltages of the battery system are being simultaneously reduced and maintained within the proper operation range.

References

[1] International Electrotechnical Commissions, "Micro grids for disaster preparedness and recovery: with electricity continuity plans and systems," Geneva Switzerland: IEC 2014, pp. 41-45, 2014.

[2] S. Katsuaki, O. Shin'ya, "Study of Micro-grid for The Cold Climates Island," *IEEE PES Asia-Pacific Power and Energy Engineering Conference(APPEEC)*, pp. 1580-1583, 2016.
DOI: https://doi.org/10.1109/APPEEC.2016.7779757

[3] Jinhong Ahn, Eel-Hwan Kim, "Implementation of a Microgrid Scheme Using a MVDC Connection between Gapado Island and Marado Island in South Korea," *The Journal on Energies*, vol. 12. pp. 1-22, 2019.
DOI: https://doi.org/10.3390/en12010187

[4] Woo-Hyun Hwang, Sang-Kyu Kim, Jung-Ho Lee, Woo-Kyu Chae, Je-Ho Lee, Hyun-Jun Lee, Jae-Eon Kim "Autonomous Micro-grid Design for Supplying Electricity in Carbon-Free Island," *Journal of Electrical Engineering and Technology*, vol. 9, no. 3, pp. 1112-1118, 2014.
DOI: https://doi.org/10.5370/JEET.2014.3.1112

[5] Sung-Sik Choi, Min-Kwan Kang, Hu-Dong Lee, Yang-Hyun Nam, Dae-Seok Rho, "A Stable Operation Strategy in Micro-grid Systems without Diesel Generators," *Journal of Electric Engineering and Technology*, Vol. 13, No. 1, pp. 114-123, 2018.
DOI: https://doi.org/10.5370/JEET.2018.13.1.114

[6] Byungki Kim, Gyung-sand Ryu, Dae-Jin Kim, Yang-Hyun Nam, Heesang Ko, Ho-Chan Kim, Sungsik Choi and Dae-Seok Rho, "A Study on the Voltage Control Method of Primary Feeder by the Energy Storage System and Step Voltage Regulator," *Journal of Science Direct*, Vol. 52, No. 2, pp. 431-436, 2019.
DOI: https://doi.org/10.1016/j.ifacol.2019.08.248

[7] Seung-Ho Kim, Sung-Sik Choi, Seung-Jong Kim, Dae-Seok Rho, "Single-phase Control Algorithm of 4-Leg type PCS for Micro-grid System," *Korea Academy Industrial Cooperation Society*, Vol. 18, No. 11, pp. 817-825, 2017.
DOI: https://doi.org/10.5762/KAIS.2017.18.11.817

[8] Yinjiao Xing, Wei He, Michael [16] Yinjiao Xing, Wei He, Michael Pecht, Kwok Leung Tsui, "State of charge estimation of lithium-ion batteries using the open-circuit voltage at various ambient temperatures," *Journal on SCI Verse Science Direct*, Vol. 113, pp. 106-115, 2014.
DOI:https://doi.org/10.1016/j.apenergy.2013.07.008

Marito Ferreira [Regular member]

• Nov. 2013 : National University of East Timor, Electrical Engineering, B.S
• Feb. 2018 : Korea University of Technology and Education, Electrical Engineering, M.S
• Sep. 2018 ~ current : Korea University of Technology and Education, Electrical Engineering, Ph.D. Student

〈Research Interests〉
Power quality analysis, micro-grid, distribution system and energy storage system

Hu-Dong Lee [Regular member]

• Aug. 2016 : Korea University of Technology and Education, Electrical Engineering, B.S
• Aug. 2018 : Korea University of Technology and Education, Electrical Engineering, M.S
• Sep. 2018 ~ current : Korea University of Technology and Education, Electrical Engineering, Ph.D. Student

〈Research Interests〉
Distribution system, power quality, coordination of protection devices, renewable energy sources and micro-grid

Jian Shen [Regular member]

• Feb. 2011 : Korea University of Technology and Education, Mechanical Engineering, B.S
• Feb. 2017 : Korea University of Technology and Education, Electrical Engineering, M.S
• March 2021 ~ current : Korea University of Technology and Education, Electrical Engineering, Ph.D. Student

〈Research Interests〉
Distribution system, power quality, energy storage system, renewable energy sources and micro-grid

Dae-Seok Rho [Life member]

• Feb. 1985 : Korea University, Electrical Engineering, B.S
• Feb. 1987 : Korea University, Electrical Engineering, M.S
• Mar. 1997 : Electrical Engineering, Hokkaido University, Ph.D.
• Mar. 1987 ~ Aug. 1998 : Korea Electrotechnology Research Institute, senior researcher
• Mar. 1999 ~ current : Korea University of Technology and Education, Electrical Engineering, professor

〈Research Interests〉
Operation of power distribution systems, dispersed storage and generation systems and power quality