A Nonlinear Droop Control for Supercapacitor-Hybrid Uninterruptible Power Supplies in DC Microgrids

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***Abstract*— Fuel cell-supercapacitor and battery-supercapacitor hybrid energy storage systems (HESS) are widely used in uninterruptible power supplies. Integral droop control is employed for managing supercapacitors, while linear droop control methods have been utilized for controlling fuel cells and batteries. However, linear droop control has excessive energy use of supercapacitors and low load-sharing performances. To address these issues, nonlinear droop control can be implemented. Nevertheless, selecting the appropriate nonlinear droop gain is crucial, as it can impact the system stability and dynamic performance of the HESS. Therefore, this conference paper proposes a nonlinear droop gain design method. By utilizing the proper nonlinear droop gain, the proposed method enhances load-sharing performance while maintaining high stability and dynamic performance. The paper demonstrates the effectiveness of the nonlinear control strategy through theoretical analysis and experimental validation.**

***Index Terms*— Droop control, DC microgrid, Supercapacitor, Uninterruptible power supply.**

I. Introduction

The increasing reliance on renewable energy sources (RESs), such as solar and wind power, has led researches into the development and optimization of direct current (DC) microgrids. These RESs offer sustainable and clean alternatives to traditional fossil fuel-based power generation. However, the intermittent nature of the RESs presents challenges to the stability and reliability of power supply in the grid, particularly in applications where a constant power supply is crucial, such as data centers, healthcare facilities, and industrial plants.

To address these challenges, uninterruptible power supply (UPS) systems have been widely adopted in critical loads to ensure a stable and continuous power supply. A key requirement for UPS systems is high energy density combined with fast dynamic response characteristics to handle rapid load fluctuations. Hybrid energy storage systems (HESS), which consist of different types of energy storage devices, have emerged as a promising solution to meet these requirements.

Common HESS configurations include fuel cell-supercapacitor (FC-SC) and battery-SC types. The FCs and batteries have high energy density, making them essential energy storage devices for UPS systems that require high energy capacity. However, their limited dynamic performance can cause significant degradation in

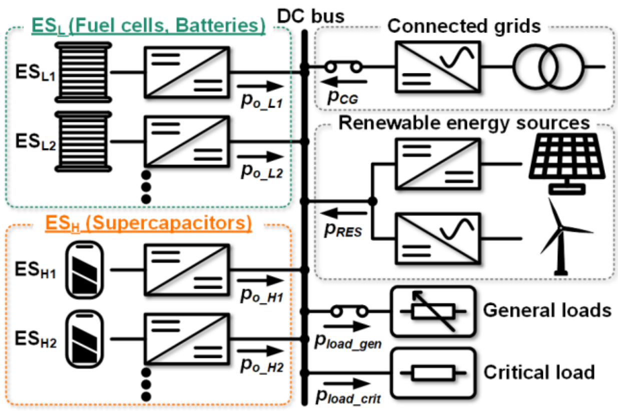


Fig. 1. Configuration of the DC microgrid system with HESSs.

their lifespan when subjected to rapid power fluctuations necessary for tracking fast load transients. Consequently, SCs with high dynamic performance are employed to complement the low dynamic performance of FCs and batteries, effectively covering rapid power changes [3]-[9].

Energy storage devices can be categorized into two main groups based on their performance characteristics. Devices with high energy density and low dynamic performance, such as FCs and batteries, are referred to as ES$_L$ (Energy Storage with Low dynamic performance). In contrast, devices with low energy density and high dynamic performance, such as SCs, are designated as ES$_H$ (Energy Storage with High dynamic performance) [3].

Conventional control strategies for HESS involve the use of linear droop control for ES$_L$ and integral droop control for ES$_H$. In this arrangement, ES$_L$ covers the low-pass filtered load, while ES$_H$ covers the high-pass filtered load. This allows the ES$_H$ to compensate for the limited dynamic performance of ES$_L$. Alongside these conventional control methods, researches have been conducted on nonlinear droop control methods, which have shown potential for improving load-sharing performance under heavy-load conditions [1]. By increasing the droop control gain for ES$_L$ in these situations, better load-sharing performance can be achieved.

Despite these advances, the application of nonlinear control methods for the HESS has yet to be thoroughly investigated in the literature. Implementing nonlinear droop control can impact the dynamic control performance

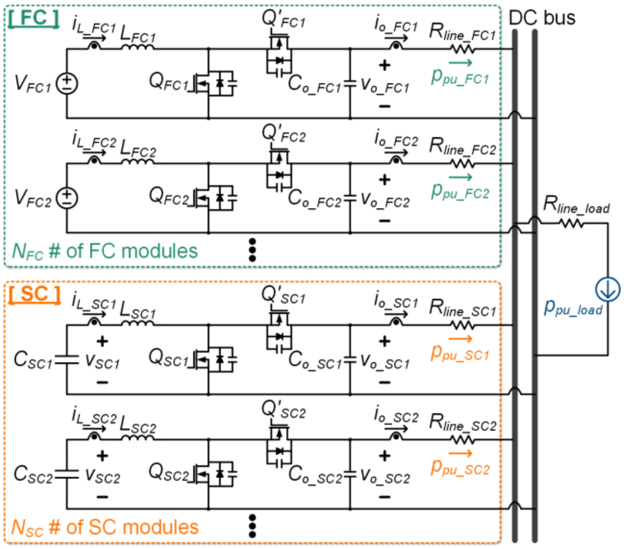


Fig. 2. Simplified model of a HESS.

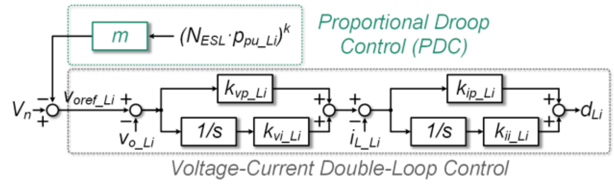


Fig. 3. Controller for ES_{Li} using the proportional droop control.

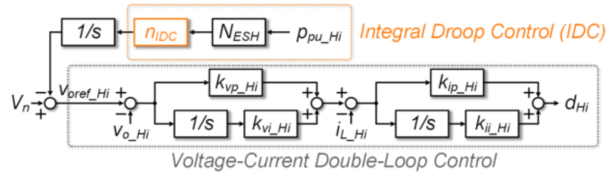


Fig. 4. Controller for ES_{Hi} using the integral droop control.

and overall system stability based on the low-pass and high-pass filtering characteristics of ES_L and ES_H, thus necessitating further exploration and discussion. This paper aims to bridge this gap by presenting the design methodology of a nonlinear droop control method for HESS and providing experimental results to validate its effectiveness.

This conference paper explores the nonlinear droop control gain in Chapter II. Chapter III focuses on the controller parameter design method, supported by simulation and experimental performance. Finally, Chapter IV provides a summary and conclusions.

II. Controller of the HESS

A. Controllers of the HESS

Fig. 1 represents a microgrid system with HESS included. As shown in the figure, RESs such as solar and wind power, connections to other grids, loads, and energy storage devices are all connected to a single microgrid DC bus. The HESS is composed of N_{ESL} ES_L modules and N_{ESH} ES_H modules. The *i-th* ES_L and ES_H modules are named ES_{Li} and ES_{Hi}, respectively. The output power of ES_{Li} and ES_{Hi} are denoted as p_{o_Li} and p_{o_Hi}, respectively. The total power that all HESS modules must output is named p_{HESS}.

It is assumed that the N_{ESL} ES_L modules have the same output power p_{o_Li}, and the N_{ESH} ES_H modules have the same output power p_{o_Hi}. Therefore, ES_L and ES_H must supply power to satisfy equation (1):

$$p_{pu\_HESS} = N_{ESL} \cdot p_{pu\_Li} + N_{ESH} \cdot p_{pu\_Hi} \tag{1}$$

Let the maximum value of p_{HESS} be P_{HESS_max}. p_{HESS}, p_{o_Li}, and p_{o_Hi} are normalized with respect to P_{HESS_max}. As a result, the per-unit power of HESS, ES_{Li}, and ES_{Hi} can be calculated as shown in equations (2), (3), and (4), respectively:

$$p_{pu\_HESS} = p_{HESS} / P_{Crit\_max} \tag{2}$$

$$p_{pu\_Li} = p_{o\_Li} / P_{Crit\_max} \tag{3}$$

$$p_{pu\_Hi} = p_{o\_Hi} / P_{Crit\_max} \tag{4}$$

Equation (1) can then be represented using equations (2)-(4) as shown in equation (5):

$$p_{pu\_HESS} = N_{ESL} \cdot p_{pu\_Li} + N_{ESH} \cdot p_{pu\_Hi} \tag{5}$$

Fig. 2 restructures the microgrid system in Fig. 1 from the HESS perspective. ES_L and ES_H typically have source voltages lower than the DC bus voltage. Therefore, boost converters, which are the simplest structure of step-up DC/DC converters, have been widely used to control their power.

Fig. 3 and Fig. 4 show the control block diagrams of the DC/DC converters for ES_{Li} and ES_{Hi}, respectively. As can be seen in the figures, they consist of a droop controller that adjusts the output voltage reference and a voltage-current double-loop controller that regulates the output voltage with the output voltage reference created by the droop controller.

In this chapter, for the sake of simplicity in the analysis, it is assumed that the voltage-current double-loop controller is stable and fast enough to follow the output voltage reference created by the droop controller. Therefore, the dynamics of the output voltage of ES_{Li} and ES_{Hi} are affected only by the droop control.

The output voltages of ES_{Li} (v_{o_Li}) and ES_{Hi} (v_{o_Hi}) are controlled as shown in equations (6) and (7):

$$v_{o\_Li} = V_n - m \cdot \left(N_{ESL} \cdot p_{pu\_Li} \right)^k \tag{6}$$

$$v_{o\_Hi} = V_n - \frac{n_{IDC}}{s} \cdot p_{pu\_Hi} \tag{7}$$

Where V_n is the nominal value of the bus voltage, and m and n are the droop controller gains of ES_{Li} and ES_{Hi}, respectively.

Assuming that v_{o_Li} and v_{o_Hi} are equal to the bus voltage (v_{Bus}), equations (6) and (7) can be equated, and equations (8) and (9) for p_{pu_Li} and p_{pu_Hi} can be derived, respectively:

$$p_{pu\_Li} = \frac{1}{N_{ESL}} \cdot \frac{\omega_{LPF}}{s+\omega_{LPF}} \cdot p_{pu\_HESS} \quad (8)$$

$$p_{pu\_Hi} = \frac{1}{N_{ESH}} \cdot \frac{s}{s+\omega_{LPF}} \cdot p_{pu\_HESS} \quad (9)$$

Where ω_{LPF} is angular cut-off frequency of the LPF as (10).

$$\omega_{LPF} = \frac{n_{IDC}}{m} \quad (10)$$

As seen in equations (8) and (9), ES_L supplies the low-pass filtered (LPF) power, while ES_H supplies the remaining high-pass filtered (HPF) power. As ω_{LPF} increases, the power distribution speed between ES_{Li} and ES_{Hi} becomes faster, and the load-following speed of ES_{Li} increases. It is necessary to adjust ω_{LPF} appropriately so that the ES_{Li} follows the load at a slower rate than their dynamic limit, preventing deterioration of their lifespan.

B. *Nonlinear Droop Control for ES_{Li}*

In this sub-chapter, the various droop profiles that can be employed in a microgrid system are discussed, including linear and nonlinear profiles.

The linear droop profile is widely used in conventional HESS control methods, particularly for the ES_L. By utilizing a constant parameter (m), the speed at which ES_{Li} follows the load can be effectively controlled. This method allows for a balance between load following and preventing the ES_L from being overburdened.

In terms of load-sharing performance analysis, it is essential to have a high small-signal output impedance for effective load sharing between ES_L modules. The linear gain method provides consistent load-sharing performance in both light and heavy load conditions. However, UPS systems typically function under heavy loads, so there may be a need to improve load sharing under these conditions, even if it means sacrificing performance under light loads.

The polynomial profile is a nonlinear method that causes the output voltage to decrease proportionally to the *k-th* power of the output power. This nonlinear method requires deriving an equivalent m for equation (10), achieved by obtaining the expression $dv_{o\_Li}/d(N_{ESL}p_{pu\_Li})$ at the operating point. Upon linearizing the method, the equivalent m at no load condition is found to be 0. However, a value of 0 for the equivalent m results in ω_{LPF} becoming infinite, making it impossible to limit the speed of changes in ES_L output power. Consequently, this method may negatively impact the lifespan of the ES_L, and is not deemed suitable for HESS control.

The inverse parabola profile is another nonlinear method that also necessitates deriving an equivalent m through linearization. With this approach, the equivalent m at no load condition is not 0, allowing for ES_L control that reflects its dynamic characteristics according to equation (10). However, this method has a drawback in that the equivalent m becomes infinite under full load conditions, resulting in system stability issues.

The piecewise linear profile, a third nonlinear method, allows for the direct design and specification of equivalent

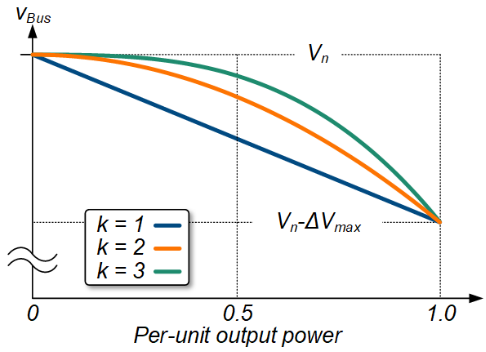


Fig. 5. V-P characteristics according to parameter k.

m values at no load and full load. In contrast to the polynomial and inverse parabola profiles, this method ensures that the equivalent m does not become 0 or infinite at no load and full load conditions [1]. As a result, the piecewise linear profile is considered the most suitable nonlinear droop control method for HESS control among the currently proposed options. This paper will describe further into analyzing the performance of the control system based on this piecewise linear profile.

The primary purpose of employing a nonlinear gain, such as the piecewise linear profile, is to increase the equivalent m under heavy-load conditions, thereby enhancing load-sharing performance. However, increasing the equivalent m in heavy-load conditions can lead to potential issues with system stability. Consequently, it is necessary to analyze system stability to determine the maximum allowable equivalent m.

Fig. 5 illustrates example nonlinear droop profiles. As the load approaches heavy-load conditions, a steeper slope is adopted to improve load-sharing performance. However, it is essential to recognize that there is a trade-off in the form of increased small-signal impedance due to the steep slope. Furthermore, a time-domain analysis of the system's operation is required to verify if the desired performance is achieved.

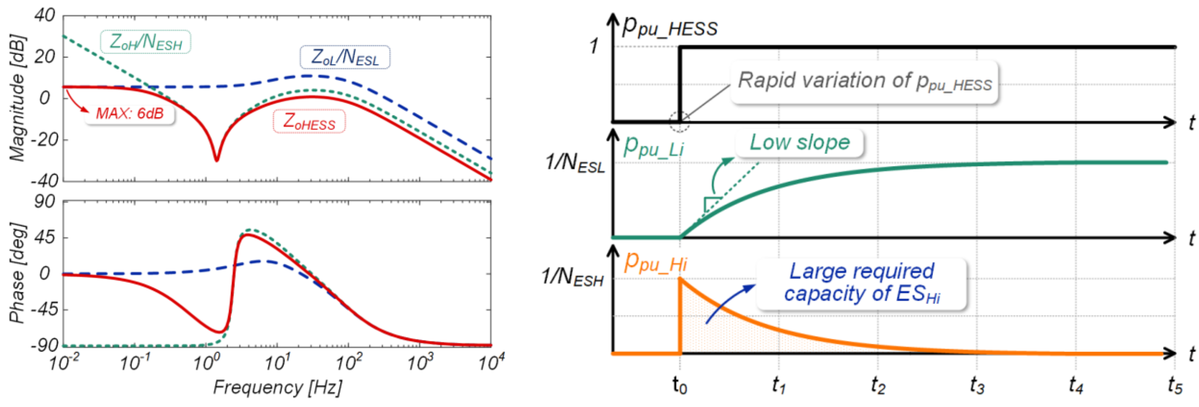
III. Verifications

A. *Stability and Dynamic Performance*

Constant power loads (CPLs) have negative impedance, which can be a risk to microgrid stability [1]-[2]. Ensuring system stability, even when loaded with CPLs, is required for the stable operation of the microgrid.

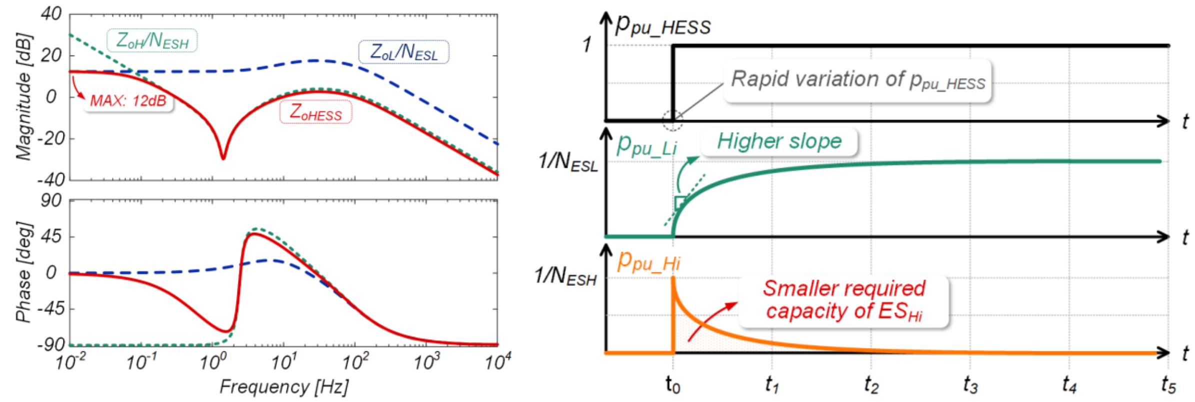
A stability analysis based on the Middlebrook stability criterion is conducted since it is one of the most conservative methods for assessing system stability. The Middlebrook stability criterion divides the system into source and load subsystems. For the system to be considered stable, the output impedance of the source subsystem must be significantly smaller than the input impedance of the load subsystem. In this paper, the source subsystem is the HESS, so the output impedance of the HESS is analyzed.

To determine the HESS's output impedance, the design of a voltage-current double-loop controller must be carried out first. The double-loop controller needs to be



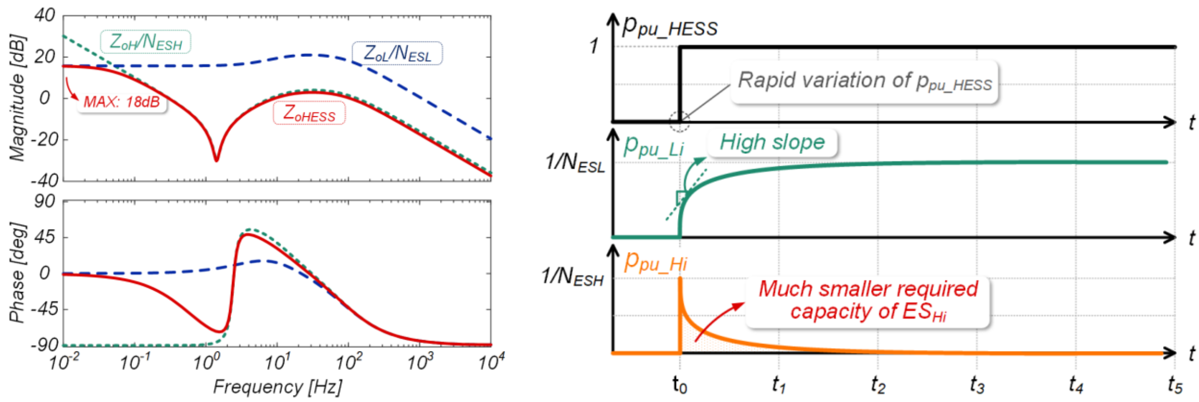
(a) (b)

Fig. 6. Characteristics of the control method when k is 1. (a) Output impedance of the HESS when the ES_{Li} supplies its rated power, (b) Key waveforms.



(a) (b)

Fig. 7. Characteristics of the control method when k is 2. (a) Output impedance of the HESS when the ES_{Li} supplies its rated power, (b) Key waveforms.



(a) (b)

Fig. 8. Characteristics of the control method when k is 3. (a) Output impedance of the HESS when the ES_{Li} supplies its rated power, (b) Key waveforms.

sufficiently stable, with minimal voltage overshoot and fast response, to allow regulation at the desired voltage set by the droop controller.

To design a sufficiently stable and fast voltage-current double-loop controller, the control parameters proposed in [4]-[5] are utilized. The parameters used for the current controller are given by (11)-(12).

$$\begin{cases} k_{ip\_Hi} = \dfrac{\omega_{i\_Hi} L_{Hi}}{V_n} \\ k_{ii\_Hi} = \dfrac{1}{10} \cdot \dfrac{\omega_{i\_Hi}^2 L_{Hi}}{V_n} \end{cases} \tag{11}$$

$$\begin{cases} k_{ip\_Hi} = \dfrac{\omega_{i\_Hi} L_{Hi}}{V_n} \\ k_{ii\_Hi} = \dfrac{1}{10} \cdot \dfrac{\omega_{i\_Hi}^2 L_{Hi}}{V_n} \end{cases} \tag{12}$$

In addition, the voltage controller parameters are given by (13)-(14).

$$\begin{cases} k_{vp\_Hi} = \dfrac{\omega_{v\_Hi} C_{o\_Hi}}{1-D_{Hi}} \\ k_{vi\_Hi} = \dfrac{1}{10} \cdot \dfrac{\omega_{v\_Hi}^2 C_{o\_Hi}}{1-D_{Hi}} \end{cases} \tag{13}$$

$$
\begin{cases} k_{vp\_Hi} = \dfrac{\omega_{v\_Hi} C_{o\_Hi}}{1 - D_{Hi}} \\ k_{vi\_Hi} = \dfrac{1}{10} \cdot \dfrac{\omega_{v\_Hi}^2 C_{o\_Hi}}{1 - D_{Hi}} \end{cases} \tag{14}
$$

Fig. 6 shows the HESS output impedance and key waveforms at full load for the linear droop gain, Fig. 7 for the piecewise linear droop with a small m at full-load condition, and Fig. 8 for the piecewise linear droop gain with a large m at full-load condition. Among the three control methods, the linear droop gain has the smallest m, resulting in the smallest HESS impedance magnitude. The control method in Fig. 8, with the largest m, has the highest impedance magnitude. Therefore, if the output impedance is designed too high in heavy-load conditions, the system may become unstable.

B. Experimental Results

In order to validate the efficacy of the proposed control strategies, a series of experiments were carried out employing a single ES_L module and a single ES_H module. Each boost converter was managed independently by its corresponding digital control unit, utilizing a TI 28069 MCU. The energy source for the ES_{Li} module was a lithium-ion battery with a rated voltage of 72V, while a 90V-rated supercapacitor served as the energy source for the ES_{Hi} module.

The experimental waveforms are presented in Fig. 9. The waveforms resulting from the traditional linear droop control technique are shown in Fig. 9(a), whereas Fig. 9(b) exhibits the waveforms obtained through the implementation of a control system employing nonlinear control methods. As load fluctuations arise, the ES_H can be observed to manage the HPF load power. The ES_L supplies LPF load power, operating at a load-following speed slower than the limits of its dynamic performance.

A comparison of the waveforms in Fig. 9(a) and Fig. 9(b) reveals that, for the linear approach, the slope of the ES_L output power decreases exponentially as it follows the load in response to rapid load variations. On the other hand, the nonlinear control method generates distinct waveforms as a result of the gain that varies according to the output power.

Given that the waveforms are influenced by the application of nonlinear gain, a comprehensive analysis of these waveforms with different nonlinear gains should be conducted to identify the most effective control method. Additional research will be performed, and the detailed design techniques for other control parameters, along with the findings, will be reported in a forthcoming journal publication.

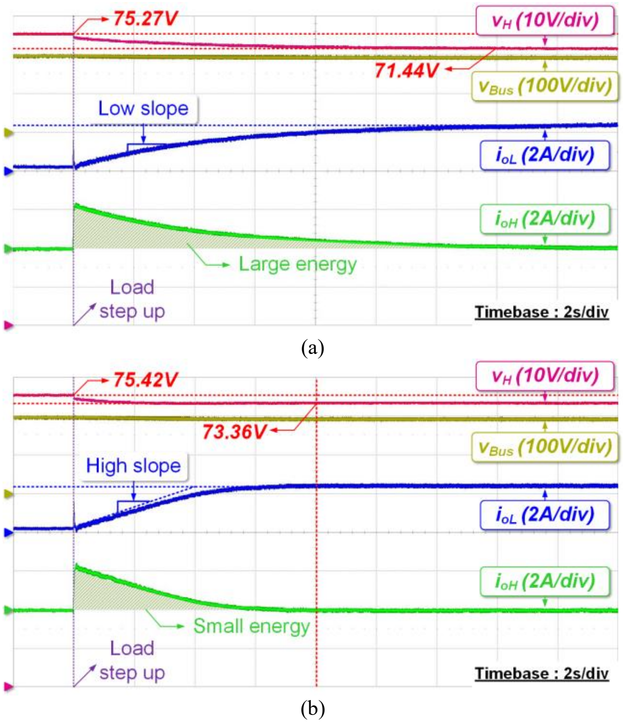


Fig. 9. Experimental waveform. (a) k=1, (b) k=2.

IV. Conclusions

To achieve both high energy density and high dynamic performance in UPS, HESS employing ES_L and ES_H in a complementary manner have become increasingly prevalent. Traditionally, linear droop control has been utilized for ES_L modules. However, in order to enhance the load-sharing performance among ES_L modules during heavy-load conditions, the implementation of nonlinear droop control should be considered. Consequently, this paper conducted a characteristic analysis of HESS with nonlinear droop control applied. Nevertheless, the piecewise linear control method exhibits transient issues at the boundaries where the gain changes. Therefore, future journal publications will present a detailed analysis and propose a continuous gain function for more accurate droop control, addressing these concerns.

Acknowledgment

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