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An Integral-Droop based Dynamic Power Sharing Control for Hybrid Energy Storage System in DC Microgrid

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Abstract—Power sharing performance is a critical issue of hybrid energy storage system (HESS) in autonomous DC microgrid (MG). In this paper, a novel integral droop (ID) is proposed to mimic dynamic characteristics of the capacitor by using energy storages (ESs) with quick response. The main advantage of the proposed controller is that dynamic power sharing among ESs is automatically realized in the decentralized level. For a given HESS, ESs with the proposed ID enables to compensate fast power change while ESs with conventional voltage-power (V - P) droop provide low frequency components of power demand. With coordinated control between ID and V - P droop, high/low pass filters (LPF/HPF) are intrinsically formulated in HESS in order to obtain reasonable dynamic power allocations among ESs. Matlab/Simulink model of HESS is established for the verification of ID controller, in which the impacts of different ID coefficients on transient performances of the system are analyzed in detail. Finally, the effectiveness of proposed ID is experimentally validated on a HIL (hardware in loop) HESS platform.

Keywords—HESS; integral droop; coordinated control; dynamic power allocation

I. INTRODUCTION

Although the renewable energy sources (RESs), such as photovoltaic power, wind turbine, and fuel cell, etc., have substantially penetrated into the power system, the inherent power output intermittency of RESs throws a serious challenge to power system reliable operation. In this regard, microgrid (MG) provides an effective way to integrate different types of distributed generations (DGs) to maximize the benefits of RESs, and meanwhile attain the system level economic operation [1]. Alternative current (AC) power transformation has been widely adopted in conventional generation, transmission, and distribution network, which thus gave rise to academic study pertaining to AC MG. However, the fact is that many RESs, energy storages (ESs) and electronic loads (such as LED light) inherently use direct current (DC), therefore, the DC MGs have become increasingly attractive due to high efficiency and controllability when compared to its AC counterpart [2].

Energy Storages (ESs) play an important role in DC MGs as the energy buffer. Normally, ESs are scheduled to mitigate power mismatch induced by the difference between the

generation of RESs and consumption of loads [3][4]. ESs can be classified according to their dynamic performances such as power density, energy density, and ramp rate. Unfortunately, no single ES is capable of fulfilling all the expected functionality. For instance, supercapacitors (SCs) have high power density but limited energy density, whereas lithium-ion batteries have high energy density but constrained ramp rate. Hence, utilization of only one type of ES to concurrently meet the sufficient energy capacity and fast power response requirements in DC MG will lead to high system design and operational cost and therefore it is not a viable solution. In this regard, hybrid energy storage system (HESS), which is considered to be a feasible and cost-effective solution, has been broadly studied to fully exploit the complementary advantages of all ESs [5].

Proper power allocation between ESs in HESS is a critical issue of system coordinated control. As reported in [6]–[8], coordinated control of HESS can be categorized into decentralized, centralized and distributed control. Centralized control is a preferred choice for MG of small scale, but the key concern with centralized control is its dependence on communication infrastructure. The system based on centralized control is prone to malfunction during severe failure and delay of communication link. Consensus algorithm implemented in distributed control bears information awareness compared to centralized control[9]. Nonetheless, convergence speed and complicated calculation requirements are the main limitations of distributed control, and it is also sensitive to the time delay of communication. Decentralized control is commonly realized using conventional V - P droop for proportional power sharing among DGs without information exchange. By using the control implemented in a decentralized fashion, the reliable and robust operation of HESS can be ensured.

High/low pass filter (HPF/LPF) plays a critical role in decoupling power demand into high/low frequency components in a decentralized way. The decoupled power is then scheduled as the current reference for the local converters. In [2], the HPF/LPF is integrated into converter control loops as virtual impedances. LPF is applied to voltage feedback loop of ESs of slow dynamics to allocate low frequency power to it, as in[10][11]. However, both types of power allocation methods suffer from redundant HPF/LPF implemented in power converters, which may cause instability of the system.

To address these concerns, integral droop (ID) based control, which is fully-autonomous and decentralized, is proposed in this paper to enhance the capacitive effect of the DC bus in microgrid. The proposed ID control works in conjunction with the traditional V - P droop control, where the ID based control is used for the fast response energy storage systems such as ultra-capacitors and the traditional V - P droop control is used for relatively slow response energy storage systems such as batteries. By using the proposed ID control, the fast ramp rate ESs have been effectively constructed as equivalent capacitors to smoothen the voltage of DC bus. The ESs deploying the ID control naturally supply or absorb burst power in the transient state, and then their power output gradually reduce to zero in steady state. However, to achieve the desired dynamic response, it is essential to have an effective co-ordination between the proposed ID and traditional V - P droop control. For the coordination between the ID and traditional V - P droop, the equivalent HPF/LPF is inherently formulated to realize the dynamic decoupling of power demand. With the proposed control, dynamic power allocation in HESS can be achieved easily and effectively without any dependence of the communication infrastructure.

This paper is organized as the following sequence. After the introduction in Section I, the configuration of DC MG and deduction from capacitor dynamic performances to the proposed integral droop controller are included in Section II. Section III presents the detailed control scheme of both ID and V - P droop for parallel connected DC/DC boost converters. Simulation results are analyzed to explicate the dynamic power sharing functionality based on the coordination of ID and V - P . Impacts of different ID droop coefficient on the transient system performance are also elaborated. An experimental prototype is built to verify the effectiveness of the proposed ID. Finally, Section IV provides the conclusions inferred for this paper.

II. SYSTEM DESCRIPTION AND INTEGRAL DROOP CONTROLLER

A. Configuration of DC MG with HESS

A generalized configuration of DC MG is shown as in Fig. 1. RESs are operated under maximum power point tracking (MPPT) mode to fully exploit the advantages of renewable and clean energy. HESS, which comprises various types of ESs, is scheduled as a buffer to be charged in case of power surplus in the system, and release energy to load when there is power deficiency. P_{Load} is assumed to be the total power consumption. The net power is normally defined as the mismatch between power generation and consumption, given by (1),

$$P_{net} = P_{RESs} - P_{Load} \quad (1)$$

Correspondingly, DC bus voltage deviation, associating with P_{net} and power generated by HESS, can be mathematically written by (2),

$$\frac{C_{sys}}{2} \frac{dV_b^2}{dt} = P_{HESS} - P_{net} \quad (2)$$

where C_{sys} represents the lumped equivalent system capacitor of DC bus, P_{HESS} and V_b are the combined output power of ESs and bus voltage, respectively. As can be seen from (2),

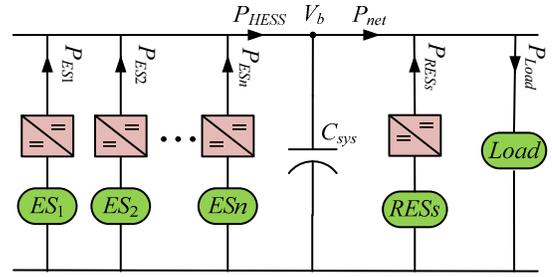


Fig. 1. DC Microgrid

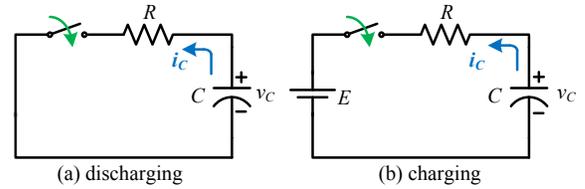


Fig. 2. Capacitor discharging/charging circuit.

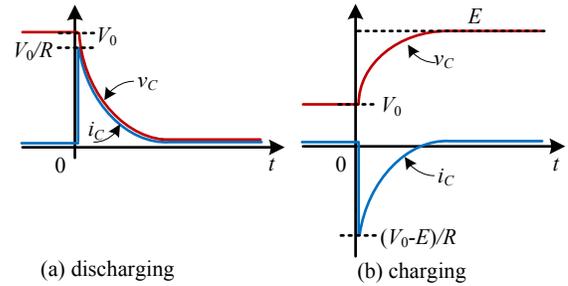


Fig. 3. Profile of voltage and current of capacitor during discharging/charging process

considering the scenario of a certain P_{net} change, V_b fluctuation diminishes if C_{sys} is properly increased, which means system capacitor helps to stabilize the bus voltage. In addition, from the perspective of small signal model of load, as reported in [9], negative impedance introduced by constant power load (CPL) possibly cause stability problem. In order to take account of the worst case, CPL is utilized hereinafter for the analysis in this paper.

B. The Proposed Integral Droop (ID)

It should be noted that C_{sys} bears the characteristics to quickly respond to the sudden change of P_{net} and therefore inhibit the sharp rise/drop of V_b . The charging and discharging circuits of a capacitor are shown in Fig. 2.

By performing KVL for discharging case in Fig. 2(a), dynamic of capacitor can be described as follow

$$RC \frac{dv_C}{dt} + v_C = 0 \quad (3)$$

where v_C , R , and C denote the capacitor voltage, series resistor, and capacitor value, respectively. Solving the differential equation (3) yields (4),

$$\begin{aligned} v_C &= V_0 e^{-t/RC} \\ i_C &= \frac{V_0}{R} e^{-t/RC} \end{aligned} \quad (4)$$

where V_0 is the initial voltage on the capacitor. Similarly, when considering charging case, voltage and current of capacitor can also be calculated as

$$\begin{aligned} v_C &= E + (V_0 - E)e^{-t/RC} \\ i_C &= \frac{V_0 - E}{R} e^{-t/RC} \end{aligned} \quad (5)$$

where E is the external DC power supply. V_0 is assumed to be smaller than E , which means the capacitor voltage will increase to E at the end of charging process. To determine the relation between the current and voltage of capacitor, both (4) and (5) can be rearranged by (6),

$$v_C = V_0 - k \int i_C dt \quad (6)$$

$k=1/C$ is a constant depicting the discharging/charging rate.

The voltage and current profiles of capacitor described by (4) and (5) are shown in Fig. 3. It can be observed that the capacitor current i_C tend to compensate by providing burst power at the instant when switch is on and exponentially approximates to zero until the end of discharging/charging process. Inspired by the equation (6) and current profile shown in Fig. 3, traditional linear V - P droop can be modified into the identical form of (6) by replacing current i_C into power value, then the proposed integral droop (ID) can be written by (7),

$$V = V_{th} - n \int P_H dt \quad (7)$$

where V_{th} is the threshold voltage as in conventional V - P droop, n is the integral droop coefficient which should be carefully designed to obtain the preferable ID dynamics, P_H refers to the high frequency component of power demand.

C. Coordination of ID and V - P droop

Combining (6) and (7), it is reasonable to infer that if a given power converter is operated under the ID controller, the output power of converter should resemble the current profile in both discharging and charging procedures as in Fig. 3. Therefore, the proposed ID is highly suitable for energy management of HESS, in which the ESs with high power density but energy limitation are supposed to respond to fast power change but work in idle condition when in steady state. Therefore, the proposed ID needs to coordinate with the conventional V - P droop, which is expressed by (8), to cooperatively supply power to load.

$$V = V_{th} - m \times P_L \quad (8)$$

In (8), P_L denotes the low frequency component of power demand which is different from the definition of P_H . m is the droop coefficient computed as

$$m = \frac{\Delta V_{max}}{P_{rating}} \quad (9)$$

where ΔV_{max} is the maximum voltage deviation allowed on DC bus, P_{rating} is the power rating of a given ES. For convenient explanation, the ID is assumed to be implemented in a class of ESs that have high ramp rate, whereas the V - P is to regulate the output voltage of converters interfaced with those ESs of restrained response ability but high energy density. Thus, the summation of P_H and P_L equal to lumped power demand P_d .

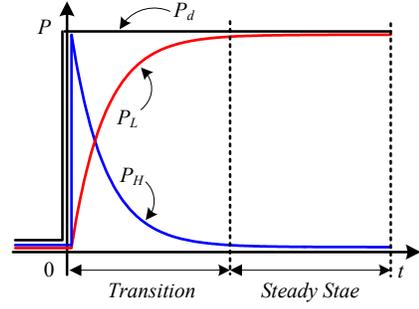


Fig. 4. Power profile of P_H , P_L and P_d

$$P_H + P_L = P_d \quad (10)$$

Combining (7) and (8) and further expressing the P_H and P_L in terms of P_d yields (11) and (12),

$$P = \frac{s}{s + n/m} P_d \quad (11)$$

$$P_L = \frac{n/m}{s + n/m} P_d \quad (12)$$

where s is Laplace operator. As can be seen from (11) and (12), the combination of ID and V - P droop naturally acts as a high/low pass filter (HPF/LPF) on power demand. P_d is thus spontaneously split into P_H and P_L , and dynamic power sharing in transit can be consequently realized without any redundant power allocation controllers.

The ratio of droop coefficients n/m is the cut-off angular frequency (ω_{cut}) of filters given by(13).

$$\omega_{cut} = \frac{n}{m} \quad (13)$$

It should be noted that by tuning the value of n/m , the transient power sharing performance among ESs can be achieved. According to (11) and (12), the expressions of P_H and P_L in time domain can be obtained by performing the inverse Laplace transform, given by (14) and (15).

$$P_H = P_d e^{-\frac{n}{m}t} \quad (14)$$

$$P_L = P_d \left(1 - e^{-\frac{n}{m}t} \right) \quad (15)$$

On the basis of (14) and (15), the illustrative power profiles of transient and steady state can be shown in Fig. 4. The

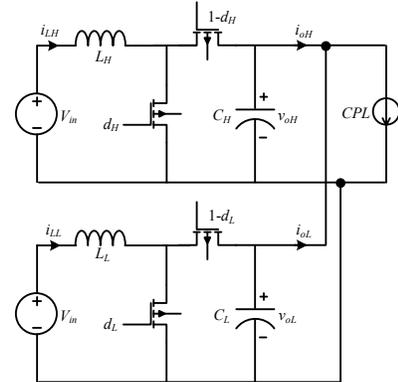


Fig. 5. Parallel-connected converters feeding constant power load employed by HESS

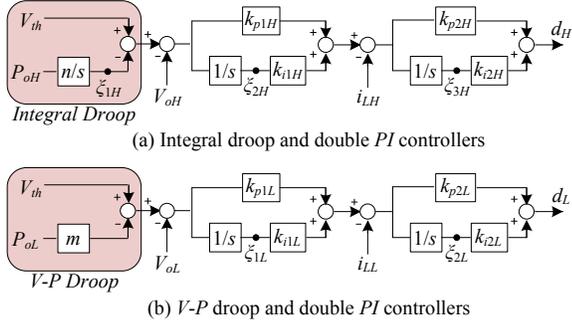


Fig. 6. Control diagram of HESS. (a) Integral droop. (b) Conventional V - P droop

coefficient n/m is the decaying rate of the exponential term, hence it indicates the dynamic response speed of the first order system given by (11) and (12). Therefore, the increase of n/m results in the fast response to load power change.

III. SIMULATION AND EXPERIMENTAL VERIFICATION OF INTEGRAL DROOP IN HESS

A. Simulation verification

The schematic layout of parallel-connected bidirectional DC/DC boost converters and corresponding ID/ V - P controllers are shown in Fig. 5. and Fig. 6, respectively. The two converters are concurrently feeding a constant power load. The subscripts H and L are subjected to the definitions in (7) and (8), which means variables accompanied by H/L associate with the proposed ID/ V - P droop controllers individually. i_{LH} and i_{LL} are the inductor current of converters which are operated in continuous current mode (CCM). The d_H and d_L are the averaged duty cycle in a switching period. The v_{oH}/v_{oL} and i_{oH}/i_{oL} are the output voltage and current respectively. P_H and P_L are the power supplied by the two boost converters, which is used to calculate the voltage reference based on (7) and (8) for double PI (proportional integral) controllers. The ξ_{1H} , ξ_{2H} , ξ_{3H} , ξ_{1L} and ξ_{2L} represent the internal state variables involved in control loops, as in Fig. 6.

Simulation results of the coordination between ID and V - P are shown in Fig. 7. As indicated by (14) and (15), the ratio of the droop coefficients (n/m) determines the response rate of the entire HESS. It is worth to mention that the coefficient m for the traditional V - P droop is commonly calculated in accordance with (9). Therefore, by tuning the value of n , different power sharing dynamics can be achieved. In this paper, different values of n/m ($0.5*2\pi$ and $1*2\pi$) are utilized to examine the impact of integral droop coefficient n on the HESS system dynamics.

As in Fig. 7, during the 1st second, the HESS has been operated in the steady condition, where the ID does not contribute any power but the V - P is scheduled to regulate DC bus voltage at around 267.5V. Step up/down of constant power load (CPL) is exerted at 1s and 3s respectively. Power sharing mechanism in both procedures of transition and steady state are displayed, and is in full agreement with the theoretical expectations.

For convenient interpretation, the two DC/DC boost converters with the ID and V - P droop controllers are simply referred as ID and V - P individually hereinafter. In the case of load step up, CPL is suddenly doubled at 1s from 250W to

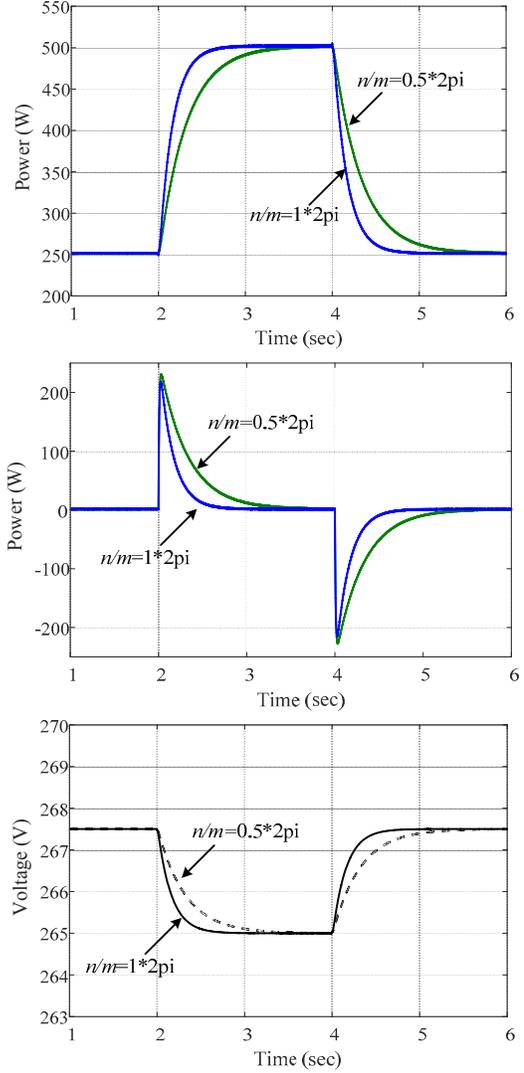


Fig. 7. Dynamic response of HESS with various n/m . (a) Output power of ID; (b) Output power of V - P droop; (c) DC bus voltage;

500W, ID enables to compensate high frequency components of P_d , and its power subsequently decreases to 0 in a short time, as illustrated in Fig. 7(a). In contrast, Fig. 7(b) presents that V - P power gradually rises from former output power of 250W to 500W in order to consistently feed the CPL and maintain DC bus voltage.

It is important to reiterate that the ratio n/m is the indication of the response speed of HESS as discussed in Section II. As can be seen from (13), n/m also portrays as the corner angular frequency of HPF/LPF as in (11)(12). This means that the higher value of n/m helps to enlarge the bandwidth of the HPF/LPF, and ID is scheduled to provide less low frequency component of P_d . Therefore, ID power value with $n/m=1*2\pi$ reduces to zero more quickly than in the case of n/m set as $0.5*2\pi$. In contrast, as in Fig. 7(b), lower value n/m of $0.5*2\pi$ drives the V - P power to gradually increase to 500W at around 2.7s. The converter response is much slower when compared to performances in case of n/m set as $1*2\pi$. Based on the analysis conducted above, this type of coordinated control is quite

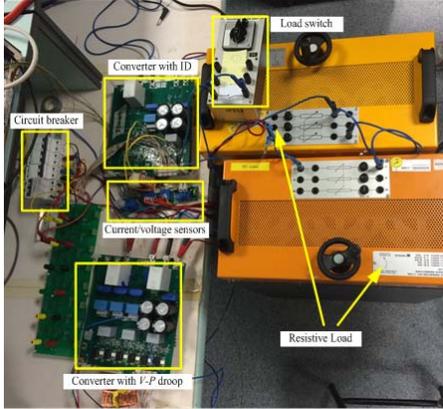


Fig. 8. Experimental platform for verification of the proposed integral droop (ID) in HESS.

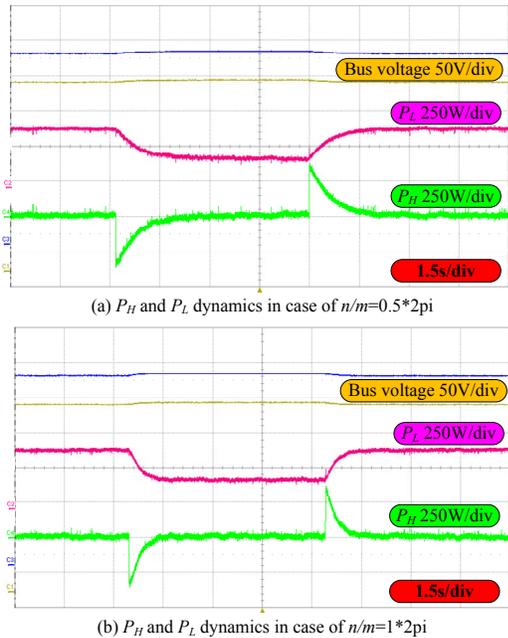


Fig. 9. Experimental results of coordination between ID and V - P droop. Dynamic power allocation in case of (a) $n/m=0.5*2\pi$ and (b) $n/m=1*2\pi$.

suitable for HESS consisting of both ESs with high and low ramp rates.

It is significant to highlight that although coordination of ID and V - P control can inherently realize the dynamic power allocation for HESS, the DC bus voltage is also influenced by the variation of n/m . A smaller value of n/m prolongs the bus voltage transition because the bus voltage is mainly regulated by the ESs with V - P which are of high energy density with limited response rate.

Identical conclusions can be drawn by exploring the dynamic power response of ID and V - P when load decrease is triggered. Variation of the ratio of n/m will accordingly affect the dynamic response of HESS, namely, smaller n/m entails longer transient duration of the system.

B. Experimental verification

An experimental platform including two bidirectional DC/DC boost converters, resistive load, and DSpace 1006 controller is built to study the effectiveness of the proposed ID, as shown in Fig. 8. Converters with ID and V - P are individually connected to supercapacitor (SC) pack and lithium-ion battery. From Fig. 9, it is easy to observe that experimental results fully agree with theoretical findings and simulations as in Fig. 7. When the load steps up/down, the power of ID increases/decreases immediately in order to compensate high frequency component of power demand and gradually reduces to zero in steady state, whereas V - P slowly responds to the load change and provides total load power during steady state. The system dynamic variations pertaining to the different ratio n/m can be also found by comparing Fig. 9(a) and (b), which justify the analysis of Section III. A. This means that the proper selection of parameters n and m will certainly help to realize desirable system performance for a given HESS.

IV. CONCLUSION

A fully-autonomous integral droop (ID) control is proposed in this paper, which is inspired by the dynamic power response of capacitors. The main idea is to revise the normal V - P droop controller to be in the identical form of charging/discharging equation of a capacitor. Therefore, by using ID, the dynamics of arbitrary ESs can be recast into characteristics of the capacitor and tend to absorb/burst high frequency power but keep immune to consistently supply power. This feature is suitable for a cluster of ESs with high ramp rate but low energy density. Coordination control between ID and conventional V - P is also proposed to realize dynamic power sharing among ESs with different response rates. Simulation and experimental results verify the effectiveness of the proposed ID control.

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