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Enhanced Dynamic Stability Control for Low-Inertia Hybrid AC/DC Microgrid With Distributed Energy Storage Systems

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ABSTRACT Hybrid ac/dc microgrids (MGs) integrated with traditional diesel generators, distributed energy storage systems (ESSs), and high penetration of renewable energy sources (RESs)-based distributed generators (DGs) have become an attractive power supply solution for isolated remote areas and islands, which can effectively reduce environmental protection pressure and improve power supply reliability. However, in such inherent low-inertia systems, randomness and fluctuation of the output power of RESs and uncertain load consumption can easily incur dynamic stability issues, such as transient power impact, unacceptable frequency deviations, and operation mode transitions for security. To solve the above problems and enhance the dynamic stability of the system, an enhanced dynamic stability control (EDSC) scheme with locally measured signals only is proposed in this paper. In this control scheme, the bi-directional interlinking dc-ac converter uses the ac frequency in ac MG as the reference value of dc voltage and adopts the current feedforward control to control the dc voltage in the dc MG to be consistent with the ac frequency. By electrically coupling dc voltage and ac frequency, power disturbances in ac or dc sides will cause almost identical variation degrees in both ac frequency and dc voltage. Under the proposed EDSC scheme, the distributed ESSs in both ac and dc sides are then automatically coordinated and controlled by the unified droop control to balance transient power disturbances and smooth output of diesel generator under normal condition, which can effectively improve stability and controllability of such low-inertia systems. Furthermore, in an emergency such as failure of diesel generator, the operation mode can be switched seamlessly with the proposed EDSC scheme. The detailed theoretical analysis including control system design, small signal model analysis of key parameter influence on system dynamics, and simulation verifications in the PSCAD/EMTDC environment is presented to verify the effectiveness and practicality of the proposed EDSC scheme.

INDEX TERMS Low-inertia hybrid ac/dc microgrids, distributed energy storage systems, enhanced dynamic stability control, transient power sharing, seamless transition.

I. INTRODUCTION

In existing remote or islanded areas where traditional diesel generators are commissioned for main power supply, fuel replenishment, high fuel emissions and pollutions, and system power supply unreliability have become prominent challenges. One feasible solution is to develop MG technology with high penetration of local RES based DGs such as photovoltaic (PV) and wind power [1]–[3]. Nevertheless, common issues associated with such MG systems, which is deemed as low-inertia ‘‘weak’’ grids, are the transient power disturbances resulted from intermittent renewable DGs and the uncertainties of load consumption, which if not properly addressed can significantly compromise the system dynamic stability and operation reliable. Distributed ESSs can be used to smooth and stabilize

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these power disturbances. Especially under major emergency situations (e.g. failure of diesel generators), they can help to achieve uninterrupted power supply for local critical loads using the seamless control mode transition by its fast-acting power electronic converters [4]–[8].

To integrate various types of renewable DGs & ac or dc loads, MG technology with hybrid ac/dc configuration may be more demanded [9]. Diesel generators, ac loads and wind power generation are generally connected to ac side of the MG, whereas PV or others dc DGs and dc loads can be integrated to dc side of the MG. The ac and dc sub-grids are usually interlinked by bi-directional dc-ac converters. ESSs can be centrally installed in ac or dc side of the MG, or distributed in different locations in both ac and dc side. The previously reported main improved dynamic stability control methods with ESSs in low-inertia MGs will be reviewed from three parts in the next: ESSs in ac MGs, ESSs in dc MGs and ESSs in a hybrid ac/dc MG.

Considering the scenarios where the ESSs are centrally connected to the ac bus, the power smoothing control of ESSs can be realized by additional control loops with the input of measured power disturbances or ac frequency. Measuring either disturbances of renewable DGs, loads, or output of diesel generators will increase more additional sensors and need fast communication which may be unreliable or introduces control latency. Moreover, the measurement and control scheme should be changed to cope with the variations of numbers, or locations of diesel generators, DGs and loads, which may reduce control system scalability and flexibility of ESSs. Thus, power smoothing control with locally measured instantaneous ac frequency has become the most accepted approach for ESSs [7]. There are two main technical schemes for frequency-based power smoothing control of ESSs. The first scheme is that the ESSs adopt basic power dispatch control, with an additional frequency support control loop to generate an incremental value in the active power reference [7], [9], [10]. In [7], a multiple-time-scales hierarchical frequency stability control strategy was proposed for medium-voltage isolated microgrid. The additional power reference included frequency-power (*f-p*) droop term and damping power term based on frequency-differential control [7]. The second approach is that the ESSs operate under power-frequency (*p-f*) droop control or virtual synchronous generator control (VSG) strategy [11], [12], to make the ESSs emulate the characteristics of synchronous generator. Thus, when there is transient power disturbance, inertial response and frequency support of ESSs for system power smoothing can be realized automatically.

When renewable DGs are mainly connected to the dc bus, centralized ESSs can be installed in dc side of the MG [9]. Power fluctuation smoothing by hybrid ESSs based on battery and ultra-capacitor had been broadly proposed in the scenarios of dc MG [13],[14], more-electric ships [8], [15] and electric vehicles [16], etc. The main objective is to use ultra-capacitors and batteries to suppress the high-frequency and low-frequency power fluctuation components respectively. In power smoothing application with multiple ESSs, adaptive transient power sharing and smoothing control considering state-of-charge (SOC) consensus was proposed in [17]. In a hybrid ac/dc MG with diesel generators, ESSs installed in dc bus with aforementioned controls can effectively smooth uncertain transient power disturbances in dc system, which can control the dc MG to act as a controlled equivalent dc voltage source. Then, if the bi-directional dc-ac interlinking converter adopts additional frequency control [9], [10], *p-f* droop control or VSG control [11], [12], power disturbances in ac system can be smoothed and dynamic stability of diesel generators can also be enhanced.

In a hybrid ac/dc MG with low-inertia, compared to centralized structure with ESSs installed in dc or ac system only, multiple distributed ESSs can be installed in both ac and dc sides, for further improvements in the system operation stability, reliability and flexibility. On one hand, when there is uncertain power disturbance in either ac or dc sub-system, local distributed ESSs can respond immediately without any control intervention. On the other hand, the probability of ESSs failure in both ac and dc sides is very low. Even if part of ESSs failed due to ac or dc faults, the rest normal ESSs in other sub-systems can still be participated in power smoothing control and the survivability of the hybrid ac/dc MG is guaranteed. In a shipboard hybrid ac/dc power system with distributed energy storages, a flexible power control strategy based on ac frequency and dc voltage droop operation features had been proposed in [18] to realize coordinated control of distributed ESSs to improve ac frequency and dc voltage stability. Under this strategy, the controls of ESSs in ac system and dc side required to receive dc voltage and ac frequency respectively through high-speed communication. In addition, power support loops of distributed ESSs and bi-directional interlinking converters with complicated design of key control parameters such as virtual inertia or capacitance may not be properly coordinated and applied. Moreover, as these distributed ESSs adopted normal power dispatch mode with additional ac frequency and dc voltage based power support loops, if diesel generator failed, ESSs' seamless transition from grid-following mode to grid-forming mode would be a challenging issue [19], unless fast operation mode detection and control system switching were adopted for distributed ESSs.

The proposed EDSC scheme in this paper aims to address the issues of transient power disturbance smoothing under normal condition and seamless operation mode transition in emergency only with conventional local control schemes which can be easily designed, implemented and respond autonomously. It focuses on MG system level to enhance dynamic stability of low-inertia hybrid ac/dc microgrid with high penetration of renewable DGs, diesel generators, and multiple distributed ESSs. The main features of the EDSC scheme are as follows:

1) The interlinking dc-ac converter controls the dc bus voltage, collecting the real-time local ac frequency (from phase-locked-loop, PLL) as the input for the dc voltage

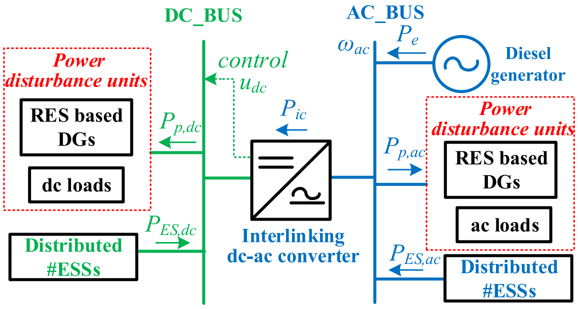

FIGURE 1. Considered low-inertia hybrid ac/dc microgrid.

reference calculation, with the purpose to achieve dynamic consensus of ac frequency and dc voltage.

2) These distributed ESSs are designed with unified droop control to share transient power disturbances autonomously to smooth the output of diesel generator and improve system frequency stability. Moreover, in an emergency, e.g. failure of diesel generator, operation mode can be realized seamlessly without communication and control system switching.

3) Through theoretical analysis and simulations, the EDSC scheme can effectively address the issues of transient power disturbance and improve the stability of the system.

The organization of the paper is as follows. Section II is the briefly description of the considered system and the main issues. Section III is to introduce the proposed EDSC scheme. Section IV develops a simplified small signal model for parameters analysis and design. Section V is simulation varication, and the last section is a conclusion of this paper.

II. CONSIDERED SYSTEM STRUCTURE AND MAIN ISSUES

In this paper, the considered low-inertia hybrid ac/dc MG with high penetration of RESs based DGs and multiple distributed ESSs is shown in Fig.1.

The diesel-engine generator is connected to the ac bus, controlling the ac voltage and frequency to be constant. The interlinking dc-ac converter is normally used to control dc voltage and maintain power balance of dc MG. RES based DGs always adopt maximum power point tracking (MPPT) control for improved generation efficiency. While limiting power control mode can be triggered for power balance and transient stability under emergency. These DGs and loads in both ac and dc sub-grids can be seen as generic power disturbance units. In this work, multiple distributed ESSs have been considered in both ac and dc MG to suppress power disturbances and smooth output of diesel generator.

The frequency dynamic of diesel generator can be shown in Fig.2. ω_{ref} is the frequency reference value; R_p and T represent static droop coefficient and integral time constant of speed governor respectively; $G_0(s)$ is equivalent transfer function of turbine dynamic;H_{ds}denotes inertia constant. P_m and P_e are mechanical and electrical power respectively.

From Fig.2, dynamic of frequency can be obtained as:

$$\Delta\omega_{ac} = -\frac{G_1(s)}{1 + G_r(s)G_0(s)G_1(s)}\Delta P_e \qquad (1)$$

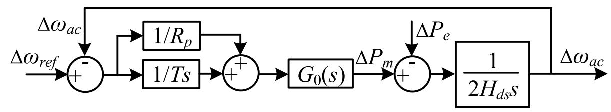

FIGURE 2. Simplified frequency dynamic of diesel generator [20].

where $G_r(s) = 1/R_p+1/Ts$, $G_1(s) = 1/2H_{ds}s$, and $G_0(s)$ can be described as $G_0(s) = (1+T_1s)/[(1+T_2s)(1+T_3s)(1+T_4s)]$ [20]. T_1, T_2, T_3, and T_4 are all related time constants of dynamics of governor and turbine.

In terms of power balance, incremental electrical power ΔP_e in (1) can be derived as

$$\Delta P_e = \Delta P_{p,ac} + \Delta P_{p,dc} - \Delta P_{ES,ac} - \Delta P_{ES,dc} \qquad (2)$$

where $\Delta P_{p,ac}$ and $\Delta P_{p,dc}$ are aggregated output power in ac and dc MG; $\Delta P_{ES,ac}$ and $\Delta P_{ES,dc}$ represent the clumped output of distributed ESSs in ac and dc side respectively. Here, loss of converters has been ignored.

It can be evidently seen that distributed ESSs have the potential to improve frequency dynamic stability and smooth output of diesel generator with appropriate control. In addition, when diesel generator fails to operate due to shortage of fuel or other unplanned faults, distributed ESSs should be seamlessly switched to grid-forming control mode for maintain power balance. Thus, how to design a simple coordinated control strategy of multiple distributed ESSs to achieve the above targets has become the most important motivation of this work.

III. PROPOSED CONTROL STRATEGY

For better illustration of the next proposed control strategy, a detailed hybrid ac/dc MG is considered, as shown in Fig.3. There is one ESS unit in each sub-MG. It should be noted the proposed control can be extended to more ESSs application.

As previously reviewed in Introduction, droop control or VSG control [11], [12] can be used for the ESSs in ac MG to smooth transient power disturbance. In [21], [22], virtual inertia control strategy for dc MGs had also been proposed to improve dc system stability. However, when implementing the methods in [11], [12], [21], [22] in the considered hybrid ac/dc MG, how to realize coordinated control of ESSs in ac and dc MGs with simple method will become a prominent challenge. Brief illustrations are shown as:

1) When normal constant dc voltage control strategy is used by the interlinking dc-ac converter, power balance in dc MG is mainly maintained by this interlinking converter. Then power disturbance in dc side can be delivered to ac system, which will incur dc voltage and ac frequency deviations. Thus, distributed ESSs in both ac and dc sides can be aware of disturbances in dc side. However, transient power sharing performance among the distributed ESSs in ac and dc subgrid will strongly rely on the dc voltage control dynamic.

2) Nevertheless, ESSs in dc MG cannot be aware of power disturbance in ac side when the interlinking dc-ac converter using traditional constant dc voltage control, due to the dc

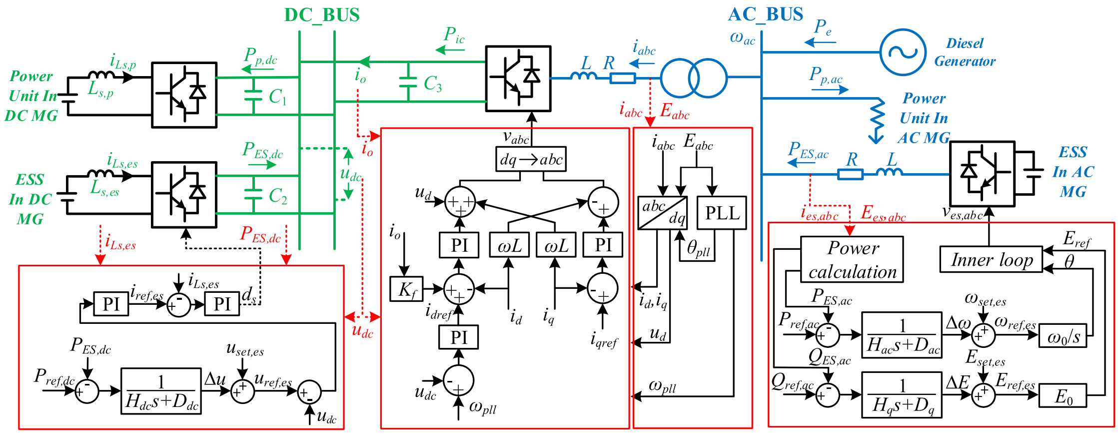

FIGURE 3. Overall proposed control strategy.

voltage will not be impacted. Unless ac frequency signal can be transmitted to ESSs in dc side by communication [18].

Thus, in order to address the aforementioned issues, a simple EDSC shown in Fig.3 has been proposed. It should be noted importantly that the proposed control uses locally measured signals only.

In the proposed control, droop method has been adopted for distributed ESSs. Under power disturbance, the generic dynamics of ESSs can be obtained as:

$$\begin{cases} \Delta P_{ES,ac} = -G_{ps,ac}(s)\Delta\omega_{ac} \\ \Delta P_{ES,dc} = -G_{ps,dc}(s)\Delta u_{dc} \end{cases} \quad (3)$$

where $G_{ps,ac}(s)$ and $G_{ps,dc}(s)$ denote dynamic responses of distributed ESSs according to ac frequency and dc voltage support control respectively, which will be introduced in next section.

For coordinated control of distributed ESSs in both ac and dc MGs, dc bus voltage u_{dc} is controlled by the interlinking dc-ac converter, with real-time detected local ac frequency ω_{pll} from phase-locked-loop (PLL) as the dc voltage reference value shown in Fig.3. Here, output current feedforward control ($i_o * K_f$) has also been adopted for the dc-ac converter, which can improve dc voltage control dynamic response significantly. Therefore, dynamic consensus of ac frequency and dc voltage can be achieved under transient, shown as:

$$\Delta\omega_{pll} \approx \Delta\omega_{ac} \approx \Delta u_{dc} \quad (4)$$

By electrically coupling dc voltage and ac frequency, power disturbances in either ac or dc side will cause almost identical variation degrees in both ac frequency and dc voltage. Thus, distributed ESSs will smooth the disturbances autonomously by droop control, with theoretical transient power smoothing and sharing performance shownin (3). It should be noted that coordinated control of multiple ESSs is realized by local signals only, without direct communication like that in [18].

In Fig.3, $P_{ref,dc}$ and $P_{ref,ac}$ are the power setting value of ESSs in dc and ac MG respectively. They are always updated from upper-level control in a hierarchical control structure,

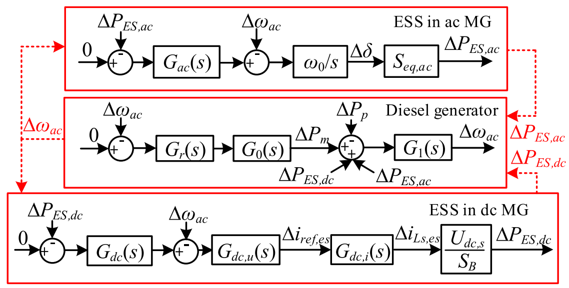

FIGURE 4. Simplified small signal model of the system shown in Fig.3.

which is out scope of this paper. In this work, we mainly focus on transient power smoothing.

IV. MODELING AND DYNAMIC STABILITY ANALYSIS

A. CONTROL SYSTEM SMALL SIGNAL MODELING

In this section, simplified small signal modeling of the hybrid ac/dc MG with the proposed control has been established, as shown in Fig.4, for further dynamic stability analysis and control parameters design.

The detailed deriving of simplified small signal modeling of ESS in ac MG with the adopted control can be found in [12]. While the dynamics of diesel generator and ESS in dc MG can be readily obtained from the control shown in Fig.2 and Fig.3. With the consensus control of dc voltage and ac frequency, and current-feedforward control, relationship in (4) can be acceptable. Thus, dc voltage control dynamic of the interlinking dc-ac converter has been ignored here.

From Fig.4, the output dynamic responses of distributed ESSs can be obtained as:

$$\begin{cases} \Delta P_{ES,ac} = -\dfrac{\omega_0 S_{eq,ac}}{s + \omega_0 S_{eq,ac} G_{ac}(s)}\Delta\omega_{ac} \\ \Delta P_{ES,dc} = -\dfrac{U_{dc,s} G_{dc,u}(s) G_{dc,i}(s)}{S_B + G_{dc}(s) G_{dc,u}(s) G_{dc,i}(s) U_{dc,s}}\Delta\omega_{ac} \end{cases} \quad (5)$$

Combined with (1), (2) and (5), following expressions can be obtained:

$$\begin{cases} \Delta\omega_{ac} = -\dfrac{G_{ds}(s)}{1+G_{ds}(s)G_{ps,dc}(s)+G_{ds}(s)G_{ps,ac}(s)}\Delta P_p \\ \Delta P_e = \dfrac{1}{1+G_{ds}(s)G_{ps,dc}(s)+G_{ds}(s)G_{ps,ac}(s)}\Delta P_p \\ \Delta P_{ES,dc} = \dfrac{G_{ds}(s)G_{ps,dc}(s)}{1+G_{ds}(s)G_{ps,dc}(s)+G_{ds}(s)G_{ps,ac}(s)}\Delta P_p \\ \Delta P_{ES,ac} = \dfrac{G_{ds}(s)G_{ps,ac}(s)}{1+G_{ds}(s)G_{ps,dc}(s)+G_{ds}(s)G_{ps,ac}(s)}\Delta P_p \end{cases} \tag{6}$$

where ΔP_p(equals to $\Delta P_{p,ac}+\ \Delta P_{p,dc}$) is the total power disturbance in the hybrid ac/dc system. Other definitions of the above related transfer functions can be seen in (7).

$$\begin{cases} G_{ds}(s) = G_1(s)/(1+G_r(s)G_0(s)G_1(s)) \\ G_{ps,dc}(s) = \dfrac{U_{dc,s}G_{dc,u}(s)G_{dc,i}(s)}{S_B+G_{dc}(s)G_{dc,u}(s)G_{dc,i}(s)U_{dc,s}} \\ G_{ps,ac}(s) = \omega_0 S_{eq,ac}/(s+\omega_0 S_{eq,ac}G_{ac}(s)) \\ G_{dc}(s) = 1/(H_{dc}s+D_{dc}) \\ G_{ac}(s) = 1/(H_{ac}s+D_{ac}) \\ S_{eq,ac} = 1.5E_{ref,es}E_{ac}\cos\delta_0/X_{eq}S_B \\ G_{dc,u}(s) = k_{pu}+k_{iu}/s \\ G_{dc,i}(s) = \dfrac{U_{dc}(k_{pi}s+k_{ii})}{s^2L_{s,es}+(k_{pi}U_{dc}+R_{s,es})s+k_{ii}U_{dc}} \end{cases} \tag{7}$$

where S_B is the power base value; $U_{dc,s}$ is the dc voltage of ESS in dc MG; U_{dc} is the stable dc bus voltage; $L_{s,es}$ and $R_{s,es}$ are filter inductance and equivalent serious resistance respectively; k_{pu} and k_{iu}, k_{pi} andk_{ii} represent the proportional gain and integral coefficient of the voltage loop and current loop respectively of ESS in dc MG. $\Delta\delta$ and X_{eq} are the increment of the power angle and equivalent reactance respectively between the output voltage of ESS in ac MG and the common ac bus; δ_0 is the stable power angle.

B. DYNAMIC STABILITY ANALYSIS

1) PERFORMANCE COMPARISION OF THE PROPOSED CONTROL AND NORMAL CONTROL

Considering the key parameters of diesel generator selected as: rated capacity is 500kW, $1/R_p = 20$, $T = 0.2$s, $H_{ds} = 2$s. Dynamic responses of frequency and diesel generator output are shown in Fig.5, under following three different controls: without ESSs, only with ESS in ac MG (with droop control shown in Fig.3), and with ESSs in both ac and dc MGs (with complete system control shown in Fig.3). In this section, all step size is 1, which means is a 100% step load disturbance.

It can be obviously seen that the proposed control based distributed ESSs can effectively reduce frequency fluctuation and smooth output of diesel generator. Detailed analysis of the impact of control parameters of ESSs on system dynamic performance and stability will be provided in the next section.

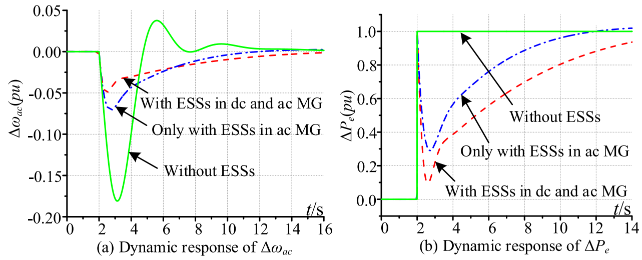

FIGURE 5. **Dynamic response of frequency and output power of diesel generator with different control under step disturbance of ΔP_p.**

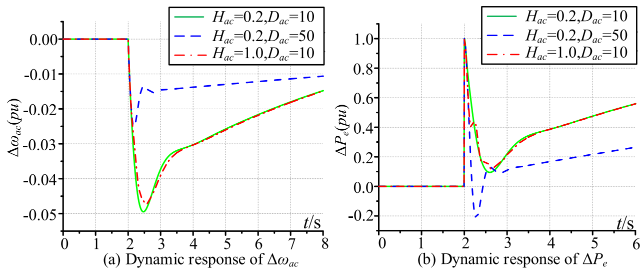

FIGURE 6. **Dynamic response of frequency and output power of diesel generator with different control parameters of ESS in ac MG under step disturbance of ΔP_p.**

2) IMPACT OF CONTROL PARAMETERS OF ESSs ON SYSTEM DYNAMIC PERFORMANCE AND STABILITY

Impact of control parameters of ESSS in AC and dc MG on the system dynamic performance and stability are shown in fig.6 and fig.7.

As shown in fig.6, increasing static droop gain D_{ac} can reduce ac frequency drop, increase system damping and smooth output of diesel generator effectively. However, a larger D_{ac} may result in a longer time for frequency recovery. While virtual inertia H_{ac} has little impact on ac frequency and power smoothing when compared to static droop gain D_{ac}. But for the very initial transient, frequency dropping rate can has been decreased by increasing virtual inertia H_{ac}.

Fig.7 shows the dynamic response of frequency and output power of diesel generator with different control parameters of ESS in dc MG. Increasing of D_{dc} can also enhance power smoothing performance and improve frequency stability significantly. A larger H_{dc} can decrease frequency changing rate, but it may also cause more oscillations. Therefore, the control parameters of ESSs in both ac and dc MGs should be carefully designed according to required power smoothing performance and system stability.

3) COORDINATED CONTROL BETWEEN ESS IN ac AND dc MG

Considering that the rated capacity of ESS in ac and dc MG satisfies $P_{ES,acB}$: $P_{ES,dcB} = \alpha : \beta$. In this work, these distributed ESSs are designed to share transient power disturbance proportionally according to this ratio. Through analysis in Fig.6 and Fig.7, it can be concluded that the static droop gain D (D_{ac} and D_{dc}) of ESSs has more important influence on power smoothing application. So, it can be readily guided

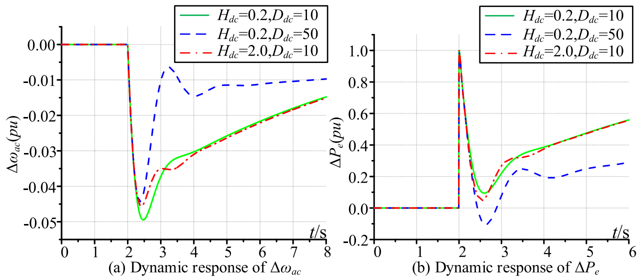

FIGURE 7. Dynamic response of frequency and output power of diesel generator with different control parameters of ESS in dc MG under step disturbance of ΔP_p.

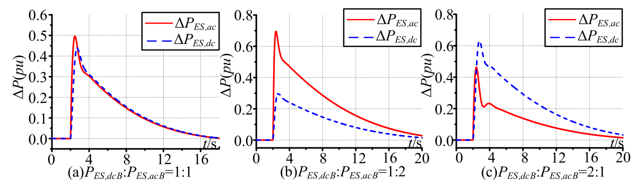

FIGURE 8. Effect of static droop gain D_{ac} and D_{dc} on the transient smoothed power sharing of ESSs.

that transient smoothed power sharing between ESSs in ac and dc MG can be realized by regulating different values of D_{ac} and D_{dc}.

The influence of static droop gains D_{ac} and D_{dc} on the coordinated power sharing of ESSs is shown in Fig.8. In Fig.8(a), considering $P_{ES,dcB}$: $P_{ES,acB}$ = 1:1, when selecting $D_{dc} = D_{ac} = 10$, the two distributed ESSs almost have the same power smoothing dynamics. When assuming $P_{ES,dcB}$: $P_{ES,acB}$ = 1: 2, and selecting $D_{dc} = 10$, $D_{ac} = 20$, it can be seen from Fig.8(b) that transient power sharing is very close to expected performance.

C. STABLE POWER SHARING OF ESSS WHEN DIESEL GENERATOR IS OUT OF OPERATION

When the diesel generator is out of operation, with the adopted droop control shown in Fig.3, these distributed ESSs can switch to grid-forming control seamlessly to maintain power balance of the hybrid ac/dc system and control ac frequency and dc voltage. From Fig.3, the relationships of outputs of ESSs and ac frequency (dc voltage) under stable state can be derived as:

$$\begin{cases} P_{ES,ac} = P_{ref,ac} - D_{ac}(\omega_{ac} - \omega_{set,es}) \\ P_{ES,dc} = P_{ref,dc} - D_{dc}(u_{dc} - u_{set,es}) \end{cases} \tag{8}$$

In terms of power balance and consensus control of ac frequency and dc voltage, the hybrid ac/dc microgrid will operate under the following stable equation:

$$\begin{cases} u_{dc} = \omega_{ac} = \omega_{set,es} + \dfrac{[P_{ref,ac} + P_{ref,dc} - (P_{p,ac} + P_{p,dc})]}{D_{ac} + D_{dc}} \\ P_{ES,ac} = P_{ref,ac} - \dfrac{D_{ac}[P_{ref,ac} + P_{ref,dc} - (P_{p,ac} + P_{p,dc})]}{D_{ac} + D_{dc}} \\ P_{ES,dc} = P_{ref,dc} - \dfrac{D_{dc}[P_{ref,ac} + P_{ref,dc} - (P_{p,ac} + P_{p,dc})]}{D_{ac} + D_{dc}} \end{cases} \tag{9}$$

TABLE 1. Main parameters of ac microgrid.

Units	Items	Parameter	Value
ESS in ac MG	Hardware parameters	LC filter	0.56mH,0.01Ω/ 270μF,0.25Ω
	Control system	$\omega_{set,es}$	1 pu
		Reference (E_0/ω_0)	311V/314.159rad/s
		$E_{set,es}/Q_{ref,ac}$	1 pu/0
		H_q/D_q	0.1/1
Diesel generator	Hardware parameters	Rated capacity	500kVA
		Rated voltage& current (L-N)	220V/757.6A
		Armature Resistance	0.003 pu
		Stator leakage reactance	0.19 pu
		D-axis &Q-axis reactance (X_d/X_q)	1.8 pu/1.8 pu
	Governor system	R_p/T	0.05/0.02s
		Time constant(T_1,T_2,T_3,T_4)	2.1s/0.2s/0.3s/7s
		Inertia ($2H_{ds}$)	4s
		ω_{ref}	1 pu

It can be seen that the ac frequency and dc voltage have droop characteristics. It should be noted that the dc voltage and ac frequency and can be recovered with low-bandwidth communication based secondary control [23], [24].

Without control system switch, these distributed ESSs can automatically change to ac frequency and dc voltage control mode. Moreover, transient power sharing among distributed ESSs still satisfies the law as designed:[6pt]

$$\begin{cases} \Delta P_{ES,ac} = \dfrac{D_{ac}(\Delta P_{p,ac} + \Delta P_{p,dc})}{D_{ac} + D_{dc}} \\ \Delta P_{ES,dc} = \dfrac{D_{dc}(\Delta P_{p,ac} + \Delta P_{p,dc})}{D_{ac} + D_{dc}} \end{cases} \tag{10}$$

With the selected static droop gains D_{ac} and D_{dc}, transient power sharing of distributed ESSs proportionally to their rated capacity can be realized in both power disturbance smoothing control mode (corresponding to normal operation) and power balance control mode (corresponding to operation mode without diesel generator).

V. SIMULATION VERIFICATION

In this section, the proposed control shown in Fig.3 has been verified by PSCAD/EMPDC based time-domain simulations. The main parameters of the hybrid ac/dc system are shown in Table 1, 2, 3, and the simulation results are all in per-unit values. Base values are: S_B = 500kVA, ω_B = 50Hz, U_{dcB} = 750V.

Simulation results in *case*1 ∼ *case*3 had been used to verify the proposed control under normal operation scenarios (corresponding to operation with diesel generator), with the same transients: when $t < 40$ s, there was ac load of 50kW (0.1 pu) only. At t = 40s, dc load of 100kW (0.2 pu) was enabled. After 25s (at t = 65s), ac load was increased to 150kW (0.3 pu). Three different power capacity ratios had been selected to test the control performance.

TABLE 2. Main parameters of dc microgrid.

Units	Items	Parameter	Value
ESS in dc MG	Hardware parameters	DC source voltage ($U_{dc,s}$)	600V
		LC filter	0.5mH,0.01Ω/ 5000μF
	Control system	Voltage setting ($u_{set,es}$)	1pu
		k_{pu}/k_{iu}	1/50
		k_{pi}/k_{iii}	0.005/5
Power Disturbance Unit	Hardware parameters	Rated capacity	500kW
		DC source voltage	600V
		LC filter	0.5mH,0.01Ω/ 5000μF
	Control system	$k_{pi,p}/k_{ii,p}$	0.0002/0.03

TABLE 3. Main parameters of interlinking dc-ac converter.

Units	Items	Parameter	Value
Interlinking dc-ac	Hardware parameters	Rated capacity	500kVA
		Rated dc&ac (L-L RMS) voltage	750V/270V
		LC filter	0.56mH,0.01Ω/ 270μF,0.25Ω
		DC side capacitance	20000uF
	Control system	PLL ($k_{p,pll}/k_{i,pll}$)	20/200
		Feedforward Coefficient (K_f)	7.5
		$k_{pu,ic}/k_{iu,ic}$	5/100
		$k_{pi,ic}/k_{ii,ic}$	1/50

A. CASE 1

In this case, assume the rated power ratio of ESSs in dc and ac MG is $P_{ES,dcB}$: $P_{ES,acB}$ = 1:1. To achieve appropriate transient smoothed power sharing, parameters of droop control of the two ESSs are selected as $H_{dc} = H_{ac} = 0.2$ and $D_{dc} = D_{ac} = 10$. In addition, power settings of $P_{ref,dc}$ and $P_{ref,ac}$ are chosen to be 0, which means these ESSs will not charge or discharge in stable state. While in real applications considering optimal operation, the power settings can be online regulated by upper energy management system (EMS). Performance of the proposed control shown in Fig.3 has been verified. Moreover, current feedforward control of the dc-ac converter has also been tested, with simulation results shown in Fig.9.

Compared with Fig.9(a) and (b), it could be found that dynamic consensus of ac frequency and dc voltage was better when control system of interlinking dc-ac converter containing feedforward than that without feedforward. And the feedforward control could also reduce the dc voltage drop caused by dc side power disturbance, which had improved the coordinated control performance of distributed ESSs. As shown in Fig.9(c), the ESSs almost shared transient power equally, as previous designed. From Fig.9(e), under power disturbance, diesel generator output had been effectively smoothed by these distributed ESSs.

B. CASE 2

In this case, assume the rated power ratio of ESSs in dc and ac MG is $P_{ES,dcB}$: $P_{ES,acB}$ = 1: 2. To achieve expected transient smoothed power sharing, parameters of droop control of the two ESSs are selected as $H_{dc} = 0.2$, $D_{dc} = 10$ and $H_{ac} = 0.4$, $D_{ac} = 20$.

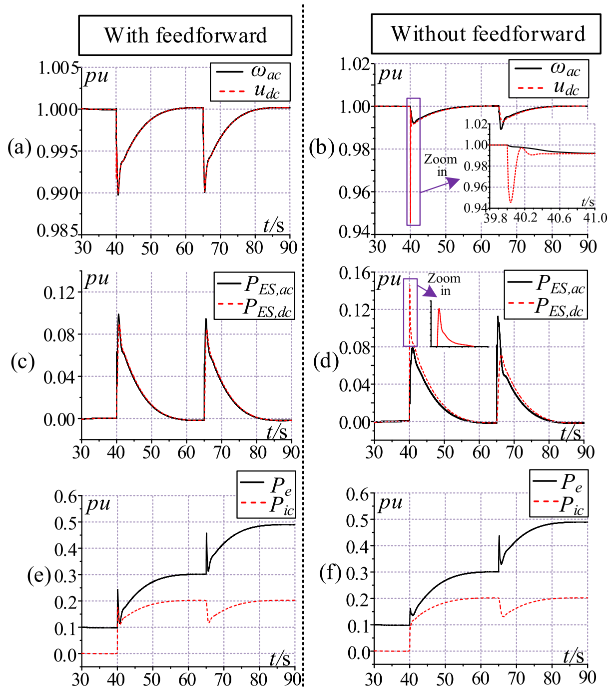

FIGURE 9. Simulation results of different control method of interlinking DC-AC in case 1.

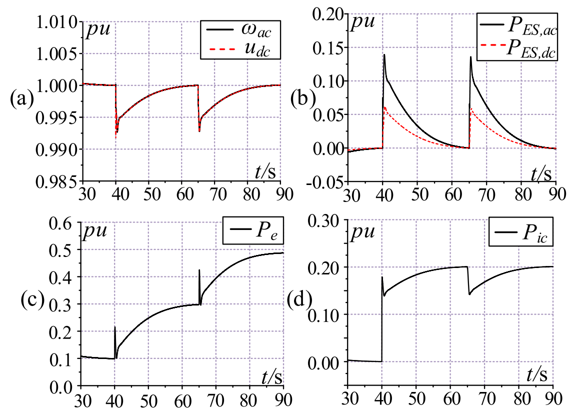

FIGURE 10. Simulation results of case 2.

With consensus control of dc voltage and ac frequency (shown in Fig.10(a)), these distributed ESSs had shared the transient power according to the rated capacity ratio, as presented in Fig.10(b), which verified the aforementioned theoretical analysis.

C. CASE 3

In this case, assume the rated power ratio of ESSs in dc and ac MG is $P_{ES,dcB}$:$P_{ES,acB}$ = 2:1. To achieve appropriate transient smoothed power sharing, parameters of droop control of the two ESSs are selected as $H_{dc} = 0.4$, $D_{dc} = 20$ and $H_{ac} = 0.2$, $D_{ac} = 10$.

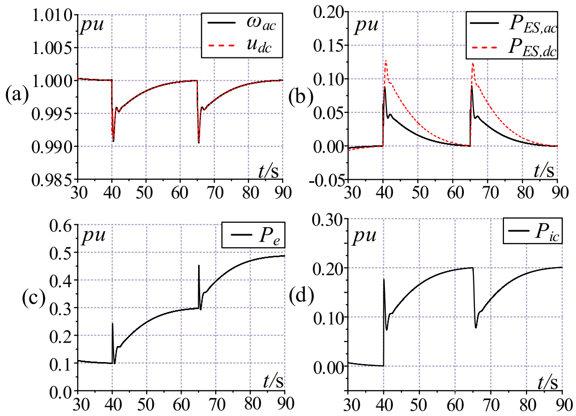

FIGURE 11. Simulation results of case 3.

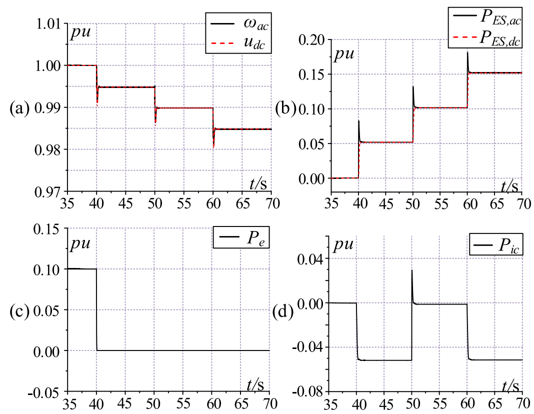

FIGURE 12. Simulation results of case 4.

As shown in Fig.11(b), the transient power shared by ESS in ac MG was almost half of that in dc MG, no matter power disturbance was occurred in either dc side or ac system.

D. CASE 4

In this case, with the proposed control, seamless transition and transient power sharing performance of distributed ESSs when the diesel generator is out of operation had been tested. The parameters of ESSs, the rated capacity ratio, and the power setting values are all the same with those in case 1. The simulation results are shown in Fig.12.

When $t < 40$s, there was only ac load of 50kW. At the time of $t = 40$s, the diesel generator is out of operation due to failure. At $t = 50$s, dc side input a load of 50kW. At $t = 60$s, the ac load increased to 100kW.

It could be seen from Fig.12 that when the diesel generator was out of operation, ESSs had been switched to grid-forming control mode seamlessly to maintain power balance of the hybrid ac/dc system. AC frequency and dc voltage had been controlled with droop characteristics. In addition, these ESSs could still share transient load demand according to their rated capacity ratio, which are consistent with the theoretical analysis. It should be noted that seamless transition control was realized without communication and control system switch.

VI. CONCLUSION

An enhanced dynamic stability control (EDSC) scheme for low-inertia hybrid ac/dc MG with distributed ESSs had been proposed in this paper, verified by both theoretical analysis and simulation results. Through simulations and comparisons, it can be figured out that current feedforward control can help to improve dc voltage dynamic response, and then realize better consensus control of ac frequency and dc voltage. Moreover, with the local measured signals based control, multiple distributed ESSs can be coordinated controlled to share the transient power disturbance and enhance dynamic stability of diesel generator. However, stability analysis and control parameters design when considering interactions of diesel generator and distributed ESSs need to be further investigated. Considering the future scenario development trend where the proportion of RES in the system is higher than the level in this paper and the diesel generator is displaced with smaller capacity, whether the controller parameters of ESSs are still appropriate and how to adjust them accordingly remain to be studied. Therefore, in the future work, the further research will be carried out around the above defects, and the proposed control strategy will be verified by experiments.

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