An Enhanced Droop Control Method for multi-source Electric Power System of More Electric Aircraft

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Abstract

The more electric aircraft concept has been identified as the major trend of future aircraft. The DC distribution network where multiple electrical sources are connected to a common HVDC bus is a promising architecture for more electric aircraft application. The power sharing of these sources is achieved using droop control. However, the conventional droop control method has a limitation in achieving accurate load sharing and voltage regulation due to the influence of the cable resistance and nominal voltage reference offset. In this paper, an enhanced droop control method is proposed for more electric aircraft application. The proposed strategy compensates the droop coefficient of each subsystem according to the estimated average total cable resistance. This is implemented with the aid of a compensating link in order to mitigate the influence of cable resistance on accurate current sharing. Also, the DC bus voltage restoration is realized by adjusting the sources references according to the product of the total load current and global droop gain with the aid of a feedforward link. The method is simple and can be easily implemented without the need for an extra communication link. The effectiveness of the proposed method has been validated through simulation.

I. Introduction

A promising solution that is expected to bring about reduced operational and maintenance cost reduced weight and fuel consumption, combat the environmental impact of greenhouse gas emission and higher energy efficiency is the movement from the conventional aircraft towards the more electric aircraft (MEA) [1, 2]. The concept of the MEA is to remove all other forms of energy (such as mechanical, pneumatic and hydraulic) but the electrical form of energy in the power distribution systems of the aircraft [1]. However, with increased electrification comes the challenge of an added complexity to the aircraft electrical power system (EPS) and the design of the onboard power generation and distribution subsystems. A possible solution is a preference for the high voltage DC (HVDC) architecture as the topology of the electrical distribution system in the MEA due to its advantages such as lower cable weight, lower losses and higher efficiency [3]. The generalised MEA EPS with HDVC configuration is shown in Fig. 1. Here, the high-pressure shaft and low-pressure shaft within an aircraft engine are each driving a permanent magnet synchronous generator (PMSG) and feeding power to a common HVDC bus via an active rectifier.

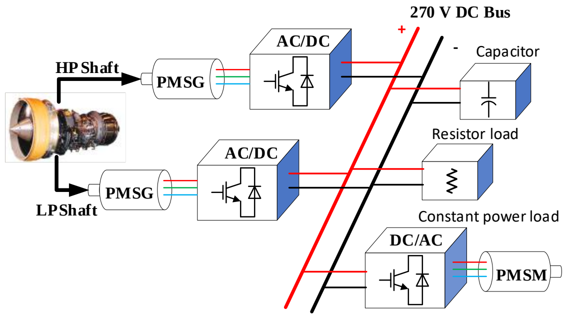


Fig. 1 Basic MEA EPS with HVDC configuration

The need to share the load power demand accurately between the parallel-connected sources shown in Fig. 1 according to their capacity cannot be overemphasised since it will impact the EPS performance. This will ensure that none of the sources is overloaded and thermally stressed. Moreover, accurate sharing of load power demand and DC bus voltage regulation is considered as the main control objectives in the low voltage DC microgrid [4]. This can be realized using the droop control method. However, the conventional droop control method has limitations in realizing accurate current sharing and DC bus voltage regulation due to the influence of the cable resistance and nominal voltage reference offset.

An enhanced voltage compensation method to independently restore the DC bus voltage to its nominal value and simultaneously achieve accurate current sharing in a droop controlled DC power system for the more electric aircraft is proposed in [5]. The proposed method can realize accurate current sharing by setting a high droop gain for each of the subsystem converter. Consequently, the global droop gain that is used to compensate for the DC bus voltage deviation is closely related to the high droop gain. The challenge with this approach is that the droop gain cannot be set arbitrarily as it is bounded by the maximum allowable DC bus voltage drop (deviation) and the power converter's full load current. Moreover, high droop gains always lead to high DC bus voltage deviation (poor power quality), especially when heavy loads are connected to the system and this is not desirable in many applications including the MEA. Also, a high droop gain has the potential of causing stability issue to the system [6, 7].

In this paper, a new enhanced droop control method that compensates the droop coefficient of each subsystem according to the estimated average total cable resistance with the aid of a compensating link in order to mitigate the influence of cable resistance on accurate current sharing is proposed. In this regard, the proposed method takes advantage of the fact that in a system such as the more electric aircraft, the cable lengths from each generator to the load can be assumed to be equal. Thus, the estimation of the average total cable resistance can be used for the droop coefficient compensation. In addition, the DC bus voltage restoration is realized through compensation by adjusting the sources references according to the product of the total load current and global droop gain with the aid of a feedforward link. The global droop gain used in this paper is closely related to the compensated droop coefficient.

II. Analysis of the Conventional Droop Control Method and Its Limitations

In this paper, we are starting with the basic MEA EPS with two sources. This will provide a general solution, with more than two sources system to be considered in the future study. The active front end converters connected in parallel and interfaced to the permanent magnet synchronous generators (PMSGs) shown in Fig. 1 can be modelled as an ideal voltage source under the droop control strategy [8]as shown in Fig. 2.

The cable is modelled as resistance for steady-state analysis and the equivalent circuit of the MEA distribution network considering only two sources is as shown in Fig. 2.

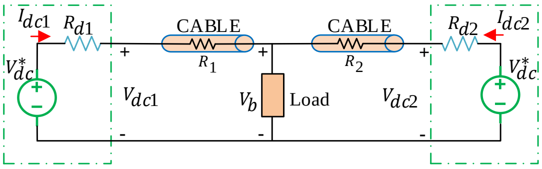


Fig. 2 Steady-state equivalent circuit of the distribution network

A. Deviation of the DC Bus Voltage

There is the existence of an unavoidable DC voltage deviation in the output of the converter due to the droop action. Furthermore, coupled with the voltage drop across the line resistance, the DC bus voltage regulation becomes deteriorated. The output voltage of the droop controlled converter in Fig. 2 is as expressed in (1).

$$V_{dci} = V^*_{dci} - R_{di} I_{dci} \tag{1}$$

where i = 1,2 represents the converter 1 and 2 respectively, V_{dc}^* is the common nominal voltage reference for each of the DC source under no-load condition, V_{dci} is the output terminal voltage of the ith DC source, R_{di} is the equivalent output resistance (or droop resistance) of the ith DC source, and I_{dci} is the output current from the ith DC source. Under the no-load condition, $V_{dc1}^* = V_{dc2}^* = V_{dc}^*$.

From (1), due to the droop action, the output voltage of each of the converter will decrease as the current output of the converters increases. Therefore, under heavy load condition, the converter output DC voltage deviation can be expressed as

$$\Delta V_{dci} = R_{di} I_{dci} = k_{di} I_{dci} \tag{2}$$

where $k_{d1}=R_{d1}$, $k_{d2}=R_{d2}$ are the droop coefficients of the individual converter connected in parallel.

However, to ensure that the voltage deviation is within an acceptable range, the maximum droop gain that can be set should be bounded by the maximum allowable voltage deviation of the DC bus voltage and the converter's full load current as expressed in (3) [8]. Also, this will ensure that the voltage regulation is within the MIL-STD-704F set standard for aircraft power system and other electrical loads [9].

$$k_{dmax} = \frac{\Delta V_{bmax}}{i_F} \tag{3}$$

where the power converter's full load current is represented as i_F, k_{dmax} is the maximum allowable droop gain and ΔV_{bmax} is the maximum allowable deviation of the DC bus voltage.

B. Degradation of Current Sharing Accuracy

When the voltage drop on the cables is considered and the voltage control dynamics are neglected, the steady-state DC bus voltage as obtained from Fig. 2 is expressed as

$$V_b = V_{dci} - R_i I_{dci} = V^*_{dc} - (k_{di} + R_i) I_{dci} \tag{4}$$

where R_i is the resistance of the cables connecting the ith DC source to the load and V_b is the main DC bus voltage. Therefore, from (4), we can obtain the expression

$$\frac{I_{dc1}}{I_{dc2}} = \frac{k_{d2}+R_2}{k_{d1}+R_1} \tag{5}$$

Hence, the current sharing ratio between the converters in steady-state is as expressed in (6), assuming the sources are supplying together.

$$I_{dc1} : I_{dc2} = \frac{1}{k_{d1}+R_1} : \frac{1}{k_{d2}+R_2} \tag{6}$$

It can be observed from (6) that the current sharing ratio of the sources will be impacted by both the cable resistance and droop gain. Furthermore, the output voltage at the terminal of the converters is not the same due to the unequal voltage drop across the unequal line resistance, hence, affecting the load current sharing accuracy.

The unequal cable impedance which is usually a common feature of a low voltage distribution system can be attributed to the difference in the relative distance between the sources and the load [8]. However, the MEA EPS distribution network in which this proposed method is desired to be applied, the generators are located at approximately the same distance (cable length) from the power distribution centre. In order words, the cable resistance from each of the generators to the load can be assumed to be identical due to the symmetrical geometry of the MEA electrical power system [5].

III. Proposed Control Method

A. DC Bus Voltage Restoration Control Strategy

To compensate for the voltage deviation associated with the main DC bus, the idea of the global droop gain was proposed in [5, 10]. Just as the individual subsystem in a multi-source system controlled by the droop control method have their droop gain, the global droop coefficient helps to define the relationship (V-I characteristics) between the main DC bus voltage and the total load current.

The DC bus voltage restoration is achieved through the addition of a common feedforward term (ΔV) to the voltage reference of each of the subsystem to regulate the sources references following the total load current as shown in Fig. 3 and Fig. 4. The feedforward term is expressed as

$$\Delta V = I_{Ldt} k_{dgn} \tag{7}$$

where I_{Ldt} represent the total load current and the global droop gain which is based on the compensated droop coefficient is k_{dgn}.

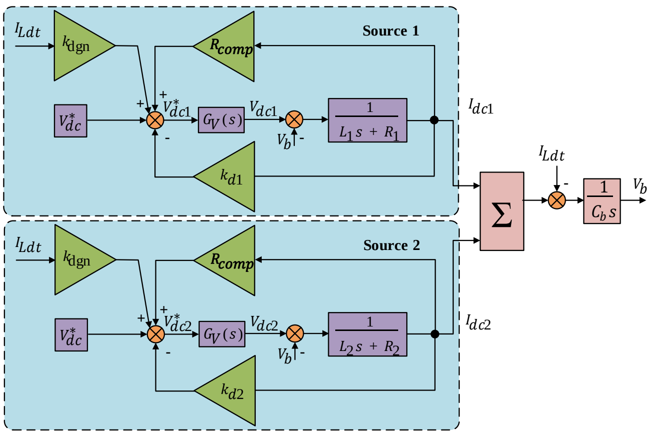


Fig. 3: Proposed control method for the voltage-mode droop control scheme

As expressed in (7), the only parameter that requires measurement is the total load current. The global droop gain is derived as follows based on the compensated or modified droop gain.

After the compensation of the droop gain, the new DC bus voltage for a two-source system can be expressed as

$$V_{bnew} = V_{dc}^{*} - (k_{d1new} + R_1)I_{dc1} = V_{dc}^{*} - (k_{d2new} + R_2)I_{dc2} \quad (8)$$

where the branch currents and their respective subsystem modified droop gains are represented as I_{dc1}, I_{dc2} and k_{d1new}, k_{d2new} respectively; the main DC bus nominal voltage is V_{dc}^{*} (270 V), and the new main DC bus voltage is V_{bnew} and the R_i is the cable resistance. Therefore, the sum of the subsystem load currents that make up the total load current for a two-source system can be expressed as

$$I_{Ldt} = I_{dc1} + I_{dc2} = (V_{dc}^{*} - V_{bnew2}) \sum_{i=1}^{2} \frac{1}{k_{dinew} + R_i} \quad (9)$$

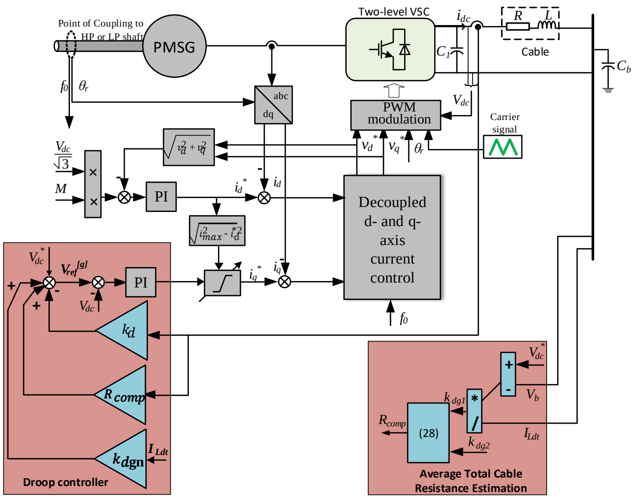


Fig. 4: Control scheme of the proposed control method implemented for the MEA Application

The expression in (9) can be rewritten as shown in (10) to show the V-I relationship between the main DC bus voltage and the total load current.

$$V_{bnew} = V_{dc}^{*} - I_{Ldt} \frac{1}{\sum_{i=1}^{2} \frac{1}{k_{dinew} + R_i}} \quad (10)$$

Hence, from (10), the global droop gain based on the compensated droop coefficient can be expressed as

$$k_{dgn} = \frac{1}{\sum_{i=1}^{2} \frac{1}{k_{dinew} + R_i}} \quad (11)$$

where k_{dgn} is global droop gain. It can be observed from (11) that the global droop gain is just the reciprocal of the sum of the compensated droop coefficient.

B. *Improved Current Sharing Control Strategy*

A common compensation term ($R_{comp}I_{dci}$) is added to the terminal voltage reference for each of the subsystem (module) with the aid of a compensating link as shown in Fig. 3 and Fig. 4. Thus, the current sharing error caused by the conventional droop control method due to the influence of the corresponding subsystems cable resistance can be compensated. Hence, improved current sharing can be realized for any desired sharing ratio.

When the compensation term is added, and the voltage control dynamics are neglected, the new steady-state DC bus voltage is expressed as

$$V_{bnew2} = V_{dc}^{*} - (k_{di} + R_i)I_{dci} + R_{comp}I_{dci} \quad (12)$$

Hence, from (12), the new or modified droop gain due to the compensation term and the new current sharing ratio for the proposed droop control method is as expressed in (13) and (14) respectively.

$$k_{dinew} = k_{di} - R_{comp} \quad (13)$$

$$I_{dc1new} : I_{dc2new} = \frac{1}{k_{d1new} + R_1} : \frac{1}{k_{d2new} + R_2} \quad (14)$$

$$R_{comp} = \frac{\sum_{i=1}^{2} R_i}{2} \quad (15)$$

where R_{comp} is the estimated average total cable resistance, $\sum_{i=1}^{2} R_i$ is the estimated total cable resistance and k_{dinew} is the modified (new) droop gain due to the introduction of the compensation term.

1) *Estimation of the Total Average Cable Resistance*

In this paper, the concept of the global droop gain proposed in [5, 10] is used in the estimation of the total cable resistance. The DC bus voltage for the conventional droop control method is expressed in (4). Therefore, for a two-source voltage droop controlled system, the DC bus voltage is expressed in (16) [10].

$$V_b = V_{dc}^{*} - (k_{d1} + R_1)I_{dc1} = V_{dc}^{*} - (k_{d2} + R_2)I_{dc2} \quad (16)$$

Hence, the sum of the subsystem branch currents that make up the total load current can be expressed as in (17).

$$I_{Ldt} = I_{dc1} + I_{dc2} = (V_{dc}^{*} - V_b) \sum_{i=1}^{2} \frac{1}{k_{di} + R_i} \quad (17)$$

where I_{Ldt} is the total load current, which can be measured on the bus bar of the EPS as shown in Fig. 4. The bus bar (main feeder) supplies power to all the loads connected to the system. The expression in (17) can be rewritten as shown in (18) to show the V-I relationship between the main DC bus voltage and the total load current.

$$V_b = V_{dc}^{*} - I_{Ldt} \frac{1}{\sum_{i=1}^{2} \frac{1}{k_{di} + R_i}} \quad (18)$$

Furthermore, the expression in (18) can be re-written as in (19) and (20).

$$V_b = V_{dc}^{*} - I_{Ldt} k_{dg1} \quad (19)$$

$$k_{dg1} = \frac{V_{dc}^{*} - V_b}{I_{Ldt}} \quad (20)$$

where k_{dg1} is the global droop gain based on the conventional droop coefficients (i.e. before compensation). Again, from (18), the global droop gain can also be expressed as in (21)

$$k_{dg1} = \frac{1}{\sum_{i=1}^{2} \frac{1}{k_{di} + R_i}} \quad (21)$$

It can be observed that the global droop gain (k_{dg1}) cannot be calculated directly from (21), this is because the corresponding subsystems resistance (R_1 and R_2) are not known. Hence, we can only achieve the value of k_{dg1} from (20). Therefore, in this paper, k_{dg1} can be obtained by the measurement of the total load current (I_{Ldt}) and DC bus voltage (V_b) as expressed in (20) and shown in Fig. 4. Furthermore, the expression of the global droop gain for the conventional droop control method in an ideal situation whereby the effect of the cable resistance is negligible is as expressed in (22).

$$k_{dg2} = \frac{1}{\sum_{i=1}^{2} \frac{1}{k_{di}}} \tag{22}$$

It can be observed from (22), that the value of k_{d2} depends on the converters droop coefficients. Since k_{d1} and k_{d2} are assigned by the controller, hence, the value of k_{dg2} can be obtained from the controller.

Now, based on the expressions of global droop gains in (21) and (22), one can develop an expression for the estimation of the total cable resistance for a multi-source droop controlled system. However, in this paper, since we are only considering two sources for ease of analysis, the total cable resistance estimation analysis is as follows.

From (21) and (22), the expressions for k_{dg1} and k_{dg2} can be re-written as in (23) and (24) respectively, for a two-source system (in this case, n = 2).

$$k_{dg1} = \frac{1}{\frac{1}{k_{d1}+R_1} + \frac{1}{k_{d2}+R_2}} = \frac{k_{d1}k_{d2} + R_1R_2 + k_{d1}R_2 + k_{d2}R_1}{k_{d1}+k_{d2}+R_1+R_2} \tag{23}$$

$$k_{dg2} = \frac{1}{\frac{1}{k_{d1}} + \frac{1}{k_{d2}}} = \frac{k_{d1}k_{d2}}{k_{d1}+k_{d2}} \tag{24}$$

By dividing the numerator and denominator of the expression in (23) by $k_{d1}k_{d2}$, we obtain the expression in (25).

$$k_{dg1} = \frac{\frac{k_{d1}k_{d2}}{k_{d1}k_{d2}} + \frac{R_1R_2}{k_{d1}k_{d2}} + \frac{k_{d1}R_2}{k_{d1}k_{d2}} + \frac{k_{d2}R_1}{k_{d1}k_{d2}}}{\frac{k_{d1}+k_{d2}}{k_{d1}k_{d2}} + \frac{R_1+R_2}{k_{d1}k_{d2}}} = \frac{1 + \frac{R_1R_2}{k_{d1}k_{d2}} + \frac{R_2}{k_{d2}} + \frac{R_1}{k_{d1}}}{\frac{1}{k_{dg2}} + \frac{R_1+R_2}{k_{d1}k_{d2}}} \tag{25}$$

Also, assuming $k_{d1} \gg R_1$ and $k_{d2} \gg R_2$, for this analysis, we obtain

$$\frac{1+0+0+0}{\frac{1}{k_{dg2}} + \frac{R_1+R_2}{k_{d1}k_{d2}}} \approx k_{dg1} \tag{26}$$

$$R_1 + R_2 \approx \left(\frac{1}{k_{dg1}} - \frac{1}{k_{dg2}}\right) k_{d1}k_{d2} \tag{27}$$

Hence, the total cable resistance can be approximated to the expression in (27) because of the assumption made earlier to ease the mathematical analysis. Now, the average total cable resistance *(R_{comp})* expressed in (15) can be re-written as in (28).

$$R_{comp} = \frac{R_1+R_2}{2} \approx \frac{\left(\frac{1}{k_{dg1}} - \frac{1}{k_{dg2}}\right) k_{d1}k_{d2}}{2} \tag{28}$$

IV. Simulation Results

The system shown in Fig. 4 is modelled using MATLAB SIMULINK© for both the conventional and proposed enhanced droop control method. The MEA EPS contains electrical loads that exhibit the behaviour of constant power load (CPL). Hence, the load can be modelled as CPL. A CPL of 20 kW is applied to the system at 0.04 s and increased by steps of +10 kW at 0.05 s, and 0.054s during the simulation. . The system parameters used for the simulations are as shown in TABLE I. The desired load sharing ratio is 1:2 based on the droop gain settings in TABLE I. The equivalent DC cable parameters used in the simulations are as shown in TALE II.

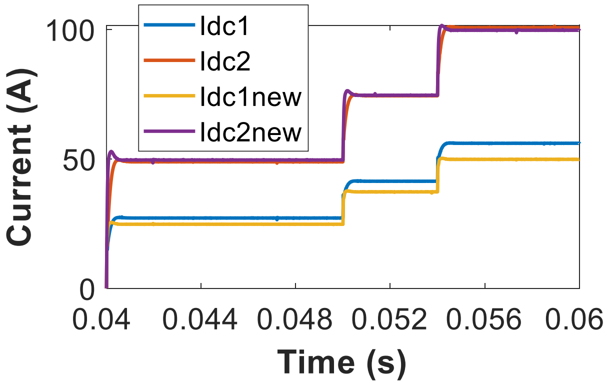
TABLE I: Electrical Power System (EPS) Parameters

Parameter	Symbol	Value
Rated Voltage of main DC Bus	V_{dc}^{*}	270 V
Local Shunt Capacitor	C_i	1.2 mF
Main DC bus capacitor	C_b	0.6 mF
Converter 1 Droop gain	k_{d1}	1/4.250
Converter 2 Droop gain	k_{d2}	1/8.500

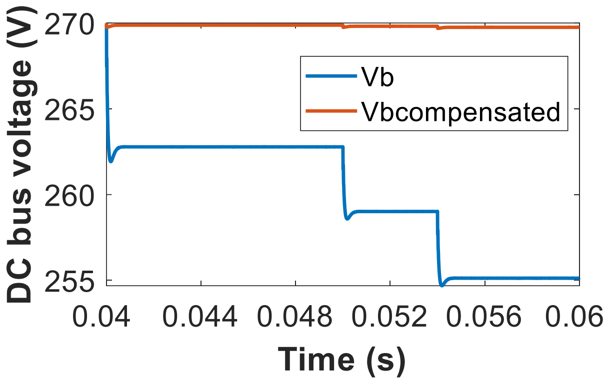
TABLE II: Equivalent DC Cables Parameters

	Resistance (R_i)-(0.6 mΩ/m)	Inductance (L_i)-(0.2 µH /m)	Length (m)
Cable 1	30 mΩ	10 µH	50
Cable 2	30 mΩ	10 µH	50

The simulation results obtained for the current sharing between the two generators using the conventional and proposed droop control method are as shown in Fig. 5 (a) and (b) for the output DC currents and DC bus voltage respectively for the desired sharing ratio of 1:2.



(a)



(b)

Fig. 5: Simulation Results for Comparing the Performance of the Conventional and the Proposed Droop Control Methods for the Desired Current Sharing Ratio (1:2) (a) DC Currents (b) DC Bus Voltage

It can be observed from Fig. 5 (a) that the output DC currents sharing between the two converters at time t = 0.054 s using the conventional droop control are I_{dc1} = 56.11 (A) and I_{dc2} = 100.7 (A). Hence, the current sharing ratio between the two converters in a steady-state using the conventional droop control methods is 1:1.8. This clearly shows that the result obtained is not in the desired sharing ratio of 1:2 and the percentage error in the current sharing ratio is calculated to be 10%. The inaccurate current sharing in the conventional droop control methods is due to the influence of the cable resistance. Conversely, the output DC currents sharing between the two converters at time t = 0.054 s using the proposed enhanced droop control are I_{dc1new} = 49.84 (A) and I_{dc2new} = 99.68 (A). Thus, the proposed droop control method can achieve the desired sharing ratio of 1:2. This shows that the average total cable resistance can effectively compensate for the effect of the corresponding subsystem cable resistance on current sharing. Also, the proposed method can reduce the output DC current flowing from each of the converters, hence, will reduce the power loss in the MEA EPS and increase its efficiency.

Furthermore, in both the conventional and proposed droop control methods, the DC bus voltage decreases as the load current increases. When a constant power load of 40 kW is applied to the system at 0.054 s, the main DC bus voltage dropped to 255.1 V (V_b) from its initial value of 270 V due to the increase in the load current for the conventional droop control method as shown in Fig. 5 (b). Conversely, It can be seen that the proposed DC bus restoration method can maintain the DC bus voltage regulation at its nominal value of 269.7 V ($V_{bcompensated}$) as shown in Fig. 5 (b).

V. Conclusion

In this paper, an enhanced droop control method for the MEA EPS application is proposed. The proposed control method can realize both accurate current sharing and significantly reduce the DC bus voltage regulation simultaneously. Due to the proposed compensation of the DC bus voltage deviation, the total load current and ultimately the output current of the converters is reduced. Hence, the approach also reduces the power losses increasing EPS efficiency. The method can be implemented easily and is independent of a communication link, thus, will save cost.

A full description of the system architecture, detailed analysis of the proposed control method, literature review and detailed simulation studies will be included in the full paper.

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