Input Series Output Parallel DC-DC Converters For Fuel Cell With BESS Application

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Abstract - Input-series-output-parallel dc–dc converters are suited for high-input voltage and low output voltage applications. This letter presents a decentralized inverse-droop control for this configuration. Each module is self-contained and no central controller is needed; thus, improving the system modularity, reliability, and flexibility. With the proposed inverse-droop control, the output voltage reference rises as the load becomes heavy. Even though the input voltages are not used in the inverse-droop loop, the power sharing including input voltage sharing and output current sharing can still be well achieved. Besides, the output voltage regulation characteristic is not affected by the variation of input voltage. The operation principle is introduced, and stability of the strategy is also revealed based on small signal modeling. Finally, the experiment is conducted to verify the effectiveness of the control strategy.

Index Terms—Input-series and output-parallel (ISOP), input voltage sharing (IVS), inverse- droop, output current sharing (OCS).

I. INTRODUCTION

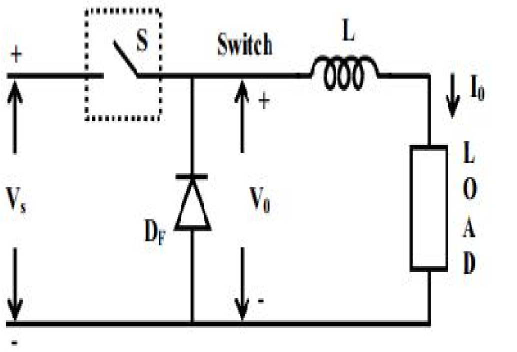
The integration of modular converters possesses the benefits of redundant operation capability, standardized modular manufacturing, and flexibility of power extension. Among them, input series-output-parallel (ISOP) configuration can offer a solution to use low-voltage rating switches in high input voltage and large output-current applications. To make the ISOP converters work properly, the power sharing including input voltage sharing (IVS) and output current sharing (OCS) must be achieved.

Many centralized controls have been proposed for the ISOP converters. With common duty ratio control [1], [2], IVS or OCS controller is not needed. However, excellent power sharing can only be achieved for modules with identical parameters. The exact sharing of the power can be achieved with the control in [3]–[10]. The relationship of IVS and OCS is revealedin [3], indicating that IVS can be achieved when OCS is obtained and vice versa. Consequently, the control strategy can be classified into three cases: IVS control [3]–[5], OCS control with IVS loops [6], and OCS control without IVS loops [7]. The decoupling IVS control schemes in [3] and [4] and the uniform input voltage distribution [5] are implemented by adding the individual IVS loops into the output voltage loop to achieve IVS. A three-loop control [6] including individual IVS loops, OCS loops, and output voltage loop is used to ensure both IVS and OCS. The cross-feedback control [7] is implemented without any input voltage feedbacks. Thus, any IVS loops can be avoided and OCS can still be achieved. However, all these aforementioned control strategies have one common feature that a central controller is needed. The reliability is reduced and the power configuration is not flexible. In [8], the central controller can be avoided, but a communication bus is required to share the information of duty cycles. The distributed control [9] also needs an input voltage bus to share IVS information. The power sharing may fail once the communication bus is interrupted, leading to lower reliability. A decentralized control [10] without communication among individual modules is used to achieve the power sharing. However, the output voltage of the converter is affected by its input voltage, and the output regulation characteristic suffers from individual input voltages especially when the total input voltage range is wide. The droop control [11] is widely used for input-parallel output- parallel (IPOP) converters. However, this conventional droop method is not stable for the ISOP converter, which is demonstrated in Sections II and III. A decentralized inverse droop control without sampling individual input voltages for ISOP dc–dc converters is proposed in this paper. With the inverse-droop method, decentralized control for ISOP modular system can be obtained, and the power sharing can be well achieved. Besides, the output regulation characteristic can be improved since the output voltage reference is not affected by the input voltage.

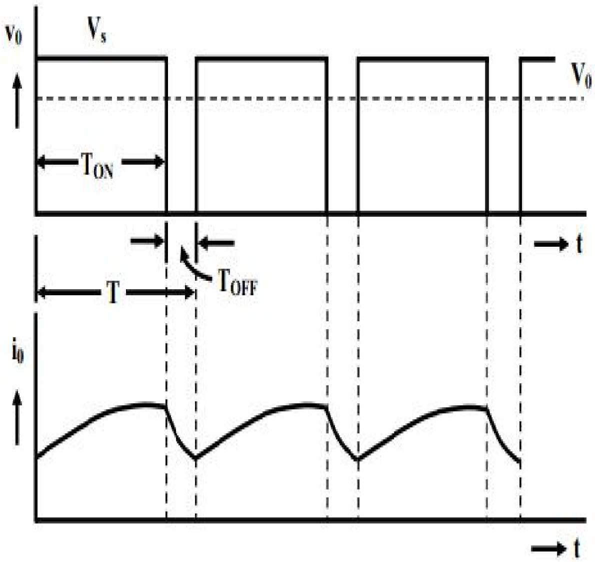
II. LITERATURE SURVEY

BUCK CONVERTERS (DC-DC)

A buck converter (dc-dc) is shown in Fig. 2a. Only a switch is shown, for which a device as described earlier belonging to transistor family is used. Also a diode (termed as free wheeling) is used to allow the load current to flow through it, when the switch (i.e., a device) is turned off. The load is inductive (R-L) one. In some cases, a battery (or back emf) is connected in series with the load (inductive). Due to the load inductance, the load current must be allowed a path, which is provided by the diode; otherwise, i.e., in the absence of the above diode, the high induced emf of the inductance, as the load current tends to decrease, may cause damage to the switching device. If the switching device used is a thyristor, this circuit is called as a step-down chopper, as the output voltage is normally lower than the input voltage. Similarly, this dc-dc converter is termed as buck one, due to reason given later.



Buck converter (dc-dc)



Output voltage and current waveforms

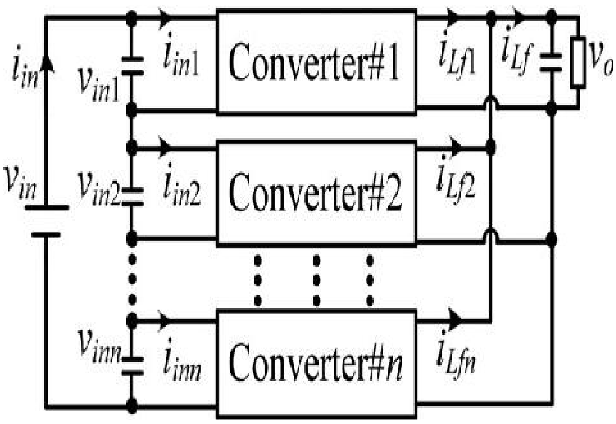
The output voltage and current waveforms of the circuit (Fig. 2a) are shown in Fig. 2b. The output voltage is same as the input voltage, i.e., 0 =Vv s , when the switch is ON, during the period, tT ≥≥ 0 . The switch is turned on at ON t = 0 , and then turned off at t= Ton. This is called ON period. During the next time interval, , the output voltage is zero, i.e., , as the diode, now conducts. The OFF period is ≥≥ TtT ON 0 v0 = DF OFF = −TTT ON , with the time period being . The frequency is ON += TTT OFF = /1 Tf . With T kept as constant, the average value of the output voltage is,

$$V_0 = \frac{1}{T}\int_0^T v_0\, dt = \frac{1}{T}\int_0^{T_{ON}} V_s\, dt = V_s\left(\frac{T_{ON}}{T}\right) = k\, V_s$$

The duty ratio is K = (Ton/T) = (Ton/ Ton+Toff), its range being 1.0>= K >= 0.0. Normally, due to turn-on delay of the device used, the duty ratio (k) is not zero, but has some positive value. Similarly, due to requirement of turn-off time of the device, the duty ratio (k) is less than 1.0. So, the range of duty ratio is reduced. It may be noted that the output voltage is lower than the input voltage. Also, the average output voltage increases, as the duty ratio is increased. So, a variable dc output voltage is obtained from a constant dc input voltage. The load current is assumed to be continuous as shown in Fig. 2b. The load current increases in the ON period, as the input voltage appears across the load, and it (load current) decreases in the OFF period, as it flows in the diode, but is positive at the end of the time period, T. k ≥≥ 0.00.1

III. PROPOSED METHOD AND RESULTS

OPERAION PRINCIPLE OF ISOP CONVERTERS WITH PROPOSED INVERSE-DROOP STRATEGY



n-module ISOP dc–dc system

The ISOP configuration consisting of *n*-module is shown in fig.6. v_{in} is total input voltage, i_{ini} (i=1,2,….n) is the input current, i_{Lfi} is the output inductor current of module #*i*. i_{lf} denotes the sum of all the output currents. Under steady state, the relationship between input voltages and output voltage can be expressed by

$V_{in\,1}\ f(D_1)= V_{in\,2}\ f(D_2)=\ldots\ldots=V_{in\,n}\ f(D_n)=V_0$ ……….(1)

where Di is the duty cycle in steady state, $f(Di)$ is the voltage gain. $Vini$ is the equilibrium value of $v_{in\,i}$(i = 1, 2 . . . n). Meanwhile, the relationship between input and output current can be written by

$I_{Lf\,1}\, f(D_1)=I_{Lf\,2}\, f(D_2)=\ldots\ldots=I_{Lf\,n}\, f(D_n)=I_{in}$………….(2)

And the power balance can be expressed as

$V_{in}\, I_{in}=V_0\, I_{Lf}$……………………(3)

where ILf 1, ILf 2 . . . ILf n , ILf , Iin , Vin , Vo are equilibrium values of iLf 1, iLf 2 . . . iLf n , iLf, iin, $v$in , vo , respectively. Based on (1)–(3), the proportion of individual output current to the total output current can be expressed by

$$M_i = I_{Lfi}/I_{Lf} = 1/\left(1+f(D_i)\sum_{j=1,j\neq i}^{n}\frac{1}{f(D_j)}\right).$$

………(4)

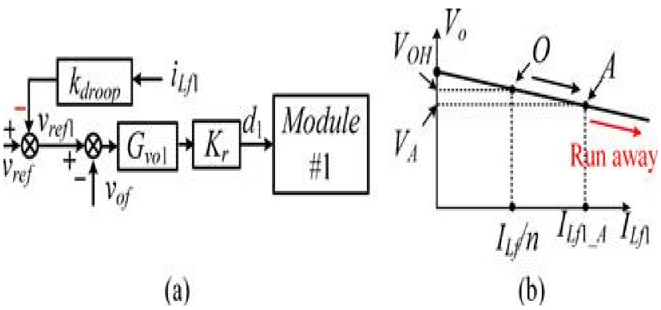
Taking module #1 as an example, this proportion coefficient versus the duty cycle can be written by

$$m_1(d_1) = 1/\left(1+f(d_1)\sum_{j=2}^{n}\frac{1}{f(D_j)}\right).$$

…… ……(5)

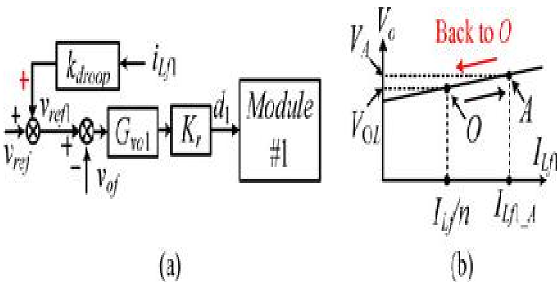
If OCS is achieved, $m1 = 1/n$. As seen from (5), $m1$ ($d1$) is a monotonous decreasing function of $f(d1)$ if the duty cycles of other modules are fixed. Generally, $f(d1)$ is an increasing function of $d1$ for converters with duty cycle control. Then, $m1$ ($d1$) will increase if the duty cycle control signal $d1$ decreases, which means module #1 shares more output current if $d1$ decreases.

The control diagram for module #1 using the conventional droop method is shown in Fig. 7(a). $Vref$ is the common voltage reference, Vref1 is the output voltage reference of module #1,Vof is the feedback of output voltage. K droop is the droop coefficient and Kr is reciprocal of the peak value of the carrier. Assuming all the modules have the same output voltage regulation characteristic and module #1 works at point "O" at steady state as shown



Conventional droop control for module #1: (a) Control diagram. (b)
Droop regulation characteristic.

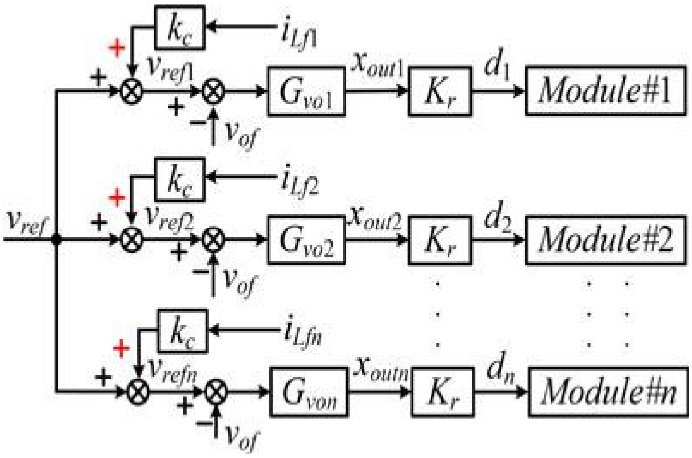
Supposing a perturbation causes the working point move to "A," namely, iLf 1 increases. The reference of output voltage $v$ref1 will decrease because the polarity of current feedback is negative. This difference will be enlarged by the voltage regulator Gvo1 . As a result, d1 will decrease. Then, module #1 will share more output current according to (5). Therefore, iLf 1 will still increase. This will enlarge the perturbation and cause a "run away" condition. In comparison, the proposed inverse-droop control for module #1 is shown in Fig. 8. kc is the inverse-droop coefficient. The difference from the conventional one is that the feedback polarity of the output current is positive instead of negative. Likewise, assuming module #1 works at the point "O" in steady state, and the working point moves to point "A" due to the perturbation. In this case, iLf 1 also increases. However, instead of decrease, the reference of output voltage will increase with the inverse-droop control. This difference will be enlarged by the voltage regulator Gvo1 . As a result, d1 will increase. Then, based on (5), iLf 1 will decrease. Finally, the working state will transfer to the steady-state point "O" again and the perturbation is rejected.



Proposed inverse-droop control for module #1: (a) Control diagram.
(b) Inverse-droop regulation characteristic.

SYSTEM STABILITY WITH THE INVERSE DROOP CONTROL STRATEGY

The proposed inverse-droop control diagram for n-module ISOP dc–dc converter is shown in Fig. 9. Xout1, Xout2, Xout$n$ are the outputs of the voltage regulators. As illustrated, there are no input voltage feedbacks and IVS loops. Thereby, the reference of the output voltage for each module does not change as the input voltage varies. Meanwhile, each module only uses its own output current and individual voltage in the control diagram; thus, it is truly decentralized and no communication is needed among the controllers.



Proposed inverse-droop control diagram for n-module ISOP DC-DC converters

An ISOP system consisting of two modules is used to demonstrate the instability of conventional droop method and analyze the stability of proposed inverse-droop strategy. The circuit topology is shown in Fig. 1(a), and the corresponding small signal circuit model is shown in Fig. 1(b).

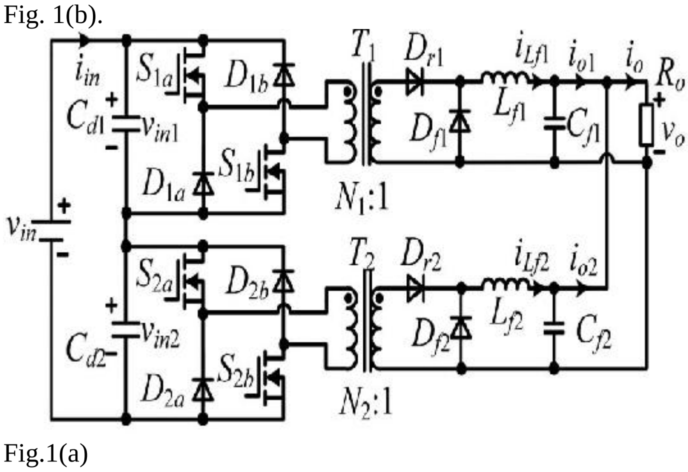


Fig.1(a)

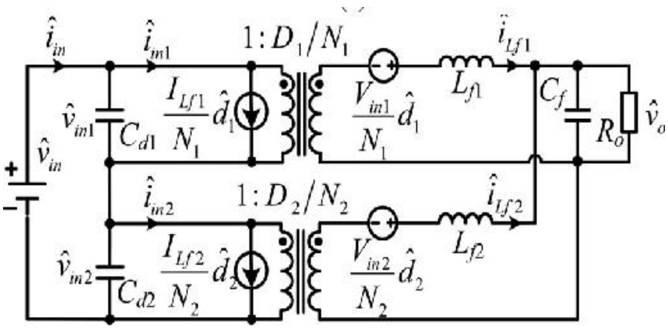


Fig.1(b)

Fig. 1. Two module ISOP converter: (a) Circuit diagram. (b) Small-signal circuit

As seen, *v*in and *vo* are the input and output voltages, *i*in , *io*1 , and *io*2 are the input and two output load currents, respectively, *D*1 and *D*2 are the equilibrium duty cycle of the two modules in steady state, *v*in1 and *v*in2 are the input voltage of each module. *vin* , ˆ*vo* ,ˆiin ˆ*io*1 ,ˆ*io*2 , ˆ *d*1 , ˆ*d*2 , ˆ*v*in1 , ˆ*v*in2 are the corresponding perturbations. *N*1 and *N*2 are the turns ratios of the transformers. Based on the small signal circuit, the following expression for module #1 can be obtained as:

$$\frac{D_1}{N_1}\hat{v}_{\text{in}1} + \frac{V_{\text{in}1}}{N_1}\hat{d}_1 = sL_{f1}\hat{i}_{Lf1} + \frac{R_o}{R_oC_fs+1}(\hat{i}_{Lf1}+\hat{i}_{Lf2})$$

……….(6)

$$\hat{i}_{\text{in}1} - \frac{I_{Lf1}}{N_1}\hat{d}_1 = \frac{D_1}{N_1}\hat{i}_{Lf1}$$

…………..(7)

Where $C_f = C_{f1} + C_{f2}$. Meanwhile,based on fig.4.the duty cycle perturbation for module #1 can be shown as

$$\hat{d}_1 = G_{vo}K_r(\hat{i}_{Lf1}k_c - \hat{v}_o k_{vf})$$

……..…(8)

Where *kvf* is the voltage feedback coefficient.

Assuming the turns ratios and inductances are identical, i.e., *N*1 = *N*2 = *N*,*Lf* 1 = *Lf* 2 = *Lf* and the duty cycles are the same in steady state, i.e., *D*1 = *D*2 = *D*, we have

$$\begin{cases} V_{\text{in}1} = V_{\text{in}2} = 0.5V_{\text{in}} \\ I_{Lf1} = I_{Lf2} = 0.5I_o. \end{cases}$$

………….(9)

Based on (6)–(9), by setting ˆ*iLf* 2 to zero, the transfer function of input current to its input voltage of module #1 is written by

$$Z_{eq1}(s) = \frac{\hat{v}_{\text{in}1}}{\hat{i}_{\text{in}1}} = \frac{A(s)}{B(s)}$$

………….(10)

Where

$$A(s) = N[2NR_oC_fL_fs^2 + (2NL_{f1} - V_{\text{in}}G_{vo}K_rk_cR_oC_f)s + 2R_oN - V_{\text{in}}G_{vo}K_rk_c + V_{\text{in}}R_ok_{vf}G_{vo}K_r] \quad (11)$$

$$B(s) = D[R_oC_f(2D + G_{vo}K_rk_cI_o)s + G_{vo}K_rk_cI_o - I_oR_ok_{vf}G_{vo}K_r + 2D].$$

………..(12)

Likewise, with the same analysis process of module #1, the impedance of module #2 can be obtained as

$$Z_{eq2}(s) = \frac{\hat{v}_{\text{in}2}}{\hat{i}_{\text{in}2}} = \frac{A(s)}{B(s)} = Z_{eq1}(s) = Z(s).$$

…………(13)

Each converter can be viewed as its equivalent impedance in parallel connection with its input dividing capacitor [12]. Due to the series connection in the input side, the input voltage difference between the two modules to the total input voltage is given by

$$\frac{\Delta\hat{v}_{12}}{\hat{v}_{\text{in}}} = \frac{\hat{v}_{\text{in}1} - \hat{v}_{\text{in}2}}{\hat{v}_{\text{in}1} + \hat{v}_{\text{in}2}} = \frac{sZ(s)(C_{d2} - C_{d1})}{2 + sZ(s)(C_{d1} + C_{d2})}.$$

…………(14)

Generally, the regulator *Gvo* in *A*(*s*) and *B*(*s*) is a PI type regulator and can be expressed as

$$G_{vo} = (k_ps + k_i)/s.$$

………………(15)

Substitution of (13) and (15) into (14) leads to the characteristic polynomial of (14) as follows:

$$\Delta q(s) = a_4s^4 + a_3s^3 + a_2s^2 + a_1s + a_0$$

……..(16)

Where the coefficients are written by

However, if the proposed inverse-droop method is implemented, *kc* is positive. Then, *a*0 is positive if *kc* is designed to be larger than *Rokvf* . For *a*4 is always positive, the Routh– Hurwitz criterion can be shown as the following expression, which is the limitation of *kp*, *ki* and *kc* to make the system stable.

$$\begin{cases} a_2a_3 - a_4a_1 > 0 \cap a_3 > 0 \\ a_1 - {a_3}^2 a_0/(a_2a_3 - a_4a_1) > 0 \cap a_0 > 0. \end{cases}$$

$$\begin{cases} a_4 = 2(C_{d1} + C_{d2})N^2R_oC_fL_f \\ a_3 = N(C_{d1} + C_{d2})(2NL_{f1} - V_{in}k_pK_rk_cR_oC_f) \\ a_2 = (C_{d1} + C_{d2})[V_{in}NK_r(k_pR_ok_{vf} - k_pk_c - k_ik_cR_oC_f \\ \quad +2R_oN^2 + 2DR_oC_f(k_pK_rk_cI_o + 2D)] \\ a_1 = k_iV_{in}NK_r(C_{d1} + C_{d2})(R_ok_{vf} - k_c) \\ \quad +2DI_o(R_oC_fk_iK_rk_c + k_iK_rk_c - R_ok_{vf}k_p) + 4D^2 \\ a_0 = 2DI_ok_iK_r(k_c - R_ok_{vf}). \end{cases}$$

……(17)

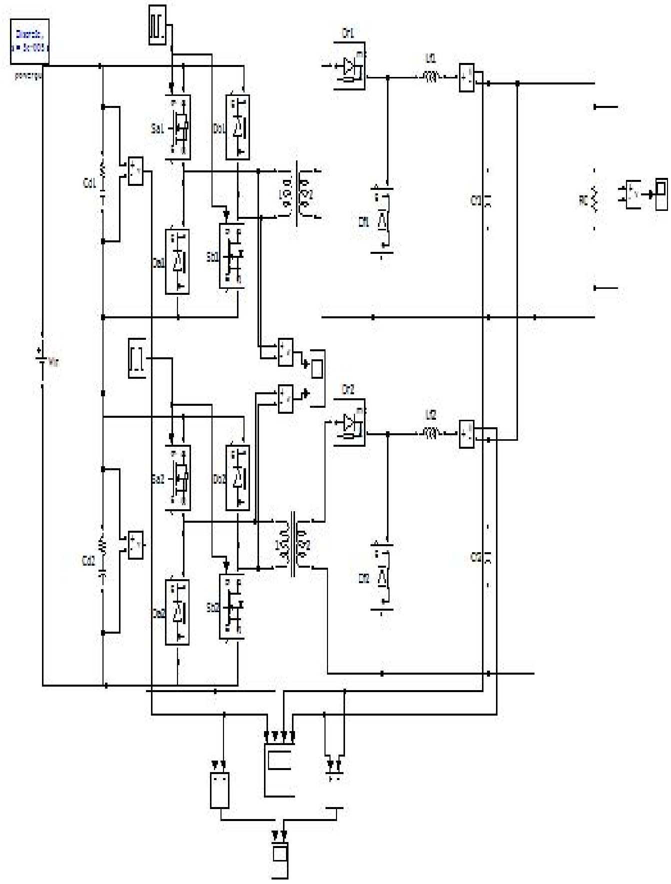
The Routh array for the characteristic polynomial shown in (17) is given by

$$\begin{array}{c|ccc} s^4 & a_4 & a_2 & a_0 \\ s^3 & a_3 & a_1 & 0 \\ s^2 & b_2 & a_0 & 0 \\ s^1 & b_1 & 0 & 0 \\ s^0 & a_0 & 0 & 0 \end{array} \qquad \begin{cases} b_2 = \frac{a_2a_3 - a_4a_1}{a_3} \\ b_1 = a_1 - \frac{a_3^2a_0}{a_2a_3 - a_4a_1}. \end{cases}$$

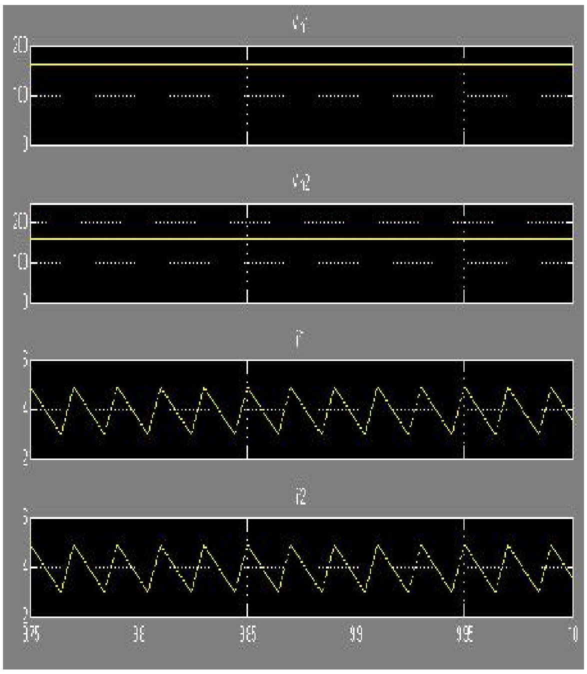
….(18)

The values in the first column of the Routh array($a4$, $a3$,$b2$, $b1$, $a0$) must all be positive in view of the Routh–Hurwitz criterion. If the conventional droop method is used, the coefficient kc in the expression of $a0$ is a negative value. Thus, $a0$ would always be negative. The conventional droop method is not stable for the ISOP system in spite of the design for compensators.

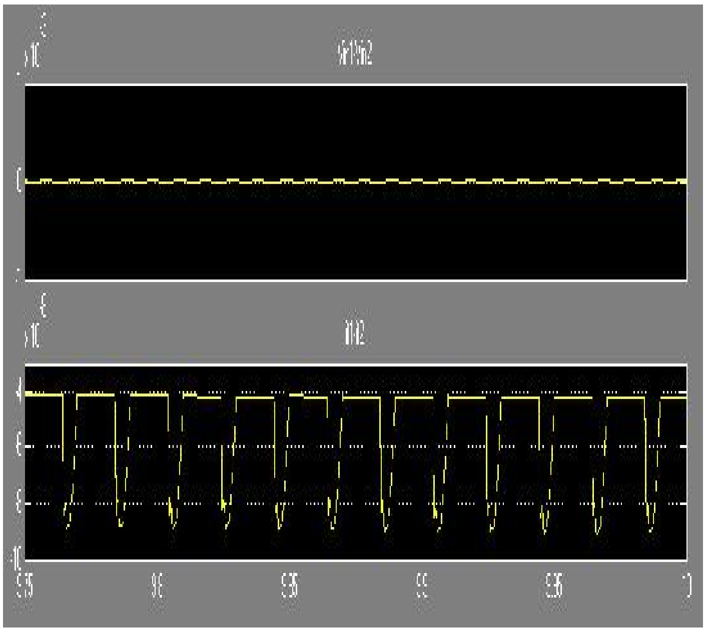
Simulink model



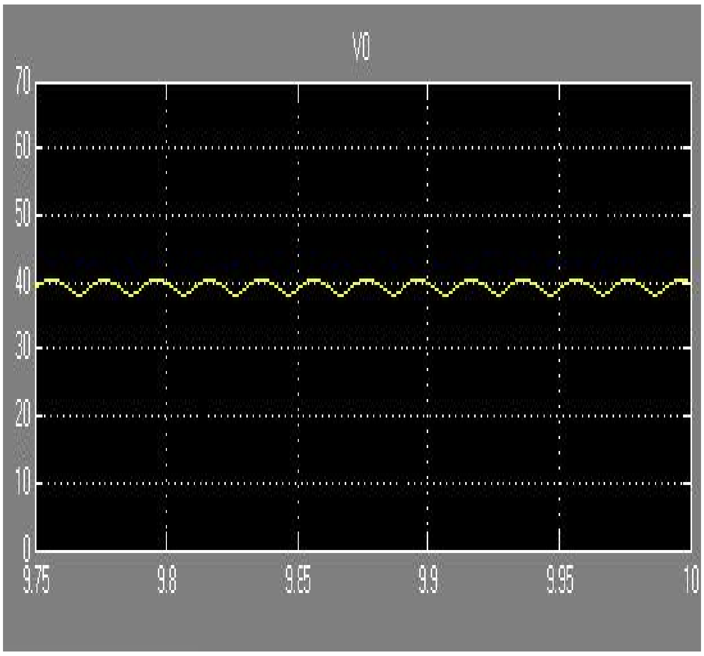
INPUT VOLTAGES AND CURRENTS:



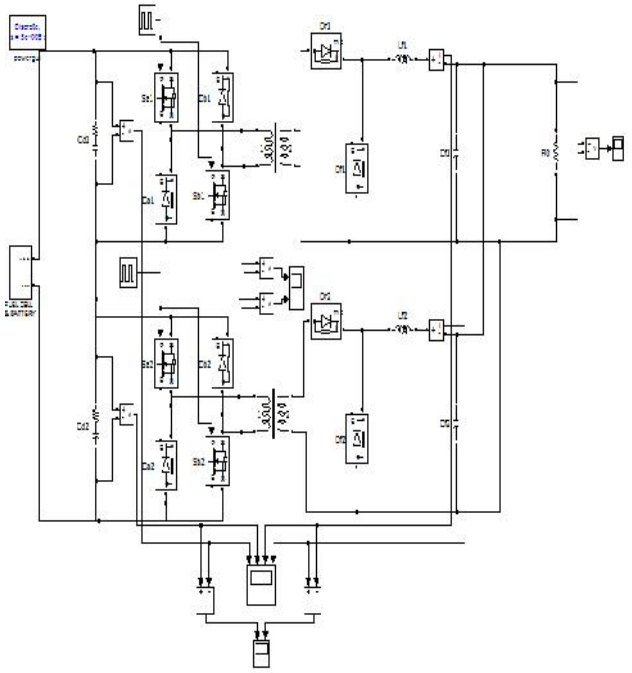
COMBINED VOLTAGES AND CURRENTS:



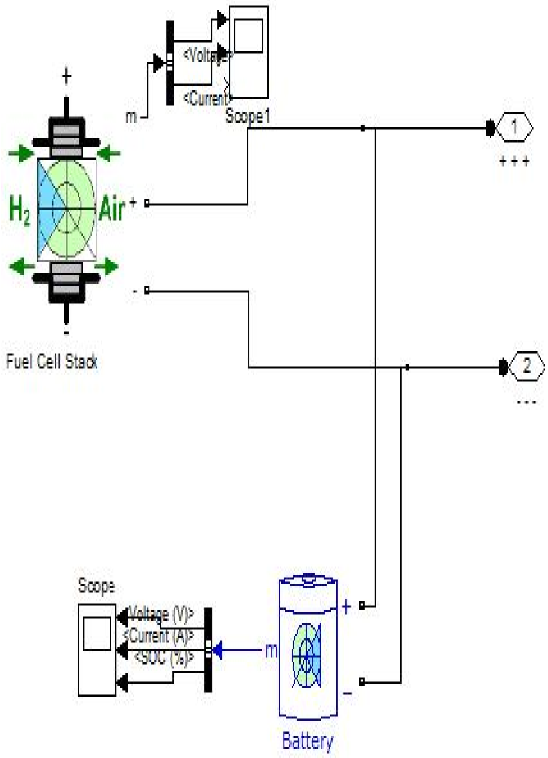
OUTPUT VOLTAGE:

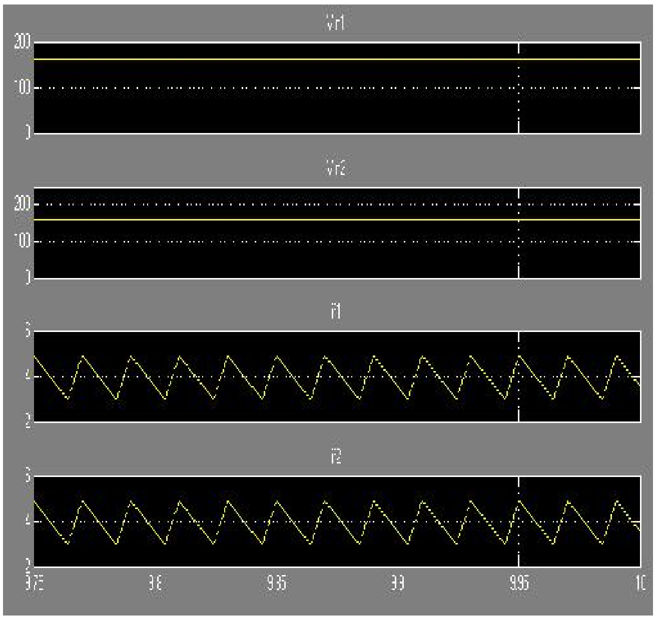


EXTENSION SIMULINK DIAGRAM:

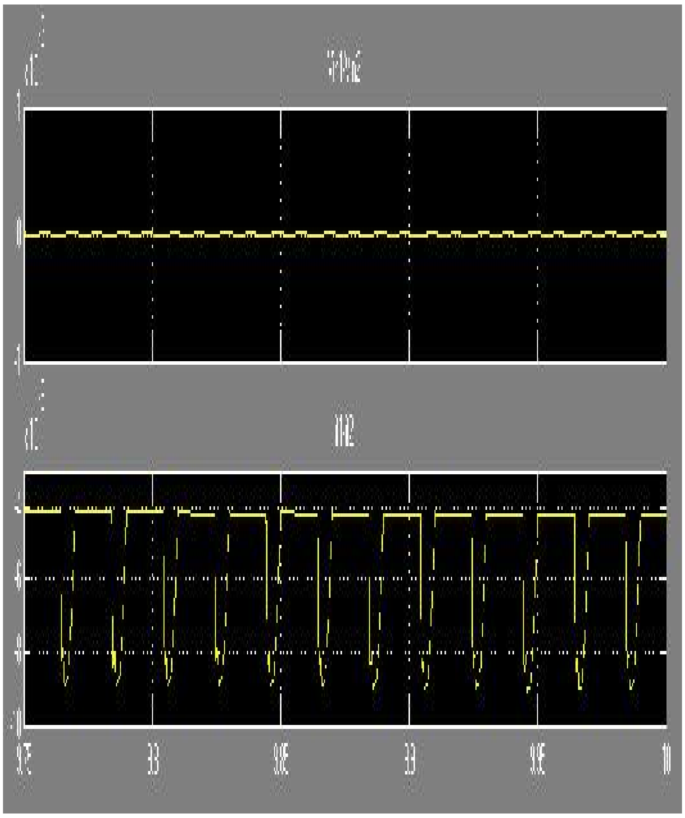


FUEL CELL AND BESS:

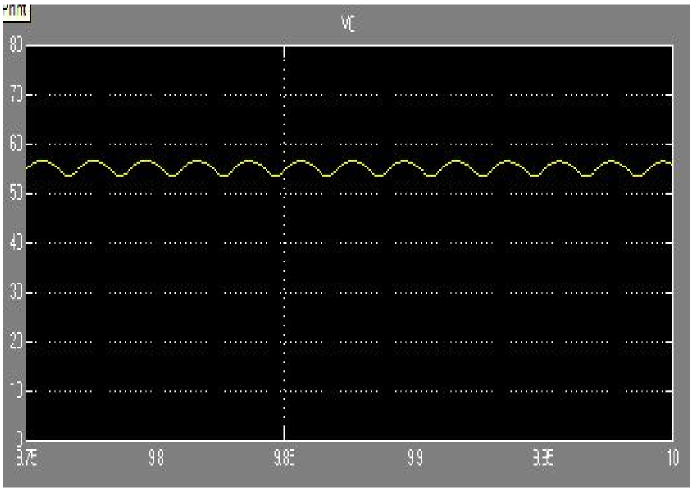




CIRCUIT VOLTAGE AND CURRENTS



FUEL CELL VOLTAGES AND CURRENTS



EXTENSION OUTPUT VOLTAGE

CONCLUSION

A decentralized inverse-droop control is proposed to achieve power sharing for ISOP dc–dc converters in this letter. Only the individual output voltages and individual output currents are needed for the inverse-droop loop and the output regulation characteristic is not affected by its input voltage. Each module is self-contained, and neither the communication bus nor extra supervisory controller is needed. Thus, the system modularity, reliability, and flexibility can be improved. Besides, the comparison between the conventional droop and proposed inverse-droop is done based on working principle analysis and small-signal modeling. The instability mechanism of the conventional droop and stability mechanism of the inverse-droop control are revealed mathematically. With the proposed control, both OCS and IVS can be achieved not only in steady state, but also in transients, even in facing with parameter mismatch. The validity of the proposed inverse-droop control is verified by the experimental results.

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