6. A NOVEL LOAD-SHARING CONTROL IN PARALLEL THREE-PHASE BOOST RECTIFIERS

6.1 EXISTING LOAD-SHARING CONTROL METHODS

The load-sharing issue in parallel converters has been addressed extensively. Generally, load-sharing mechanisms can be classified into two categories: master/slave and droop. Both concepts have merits and limitations in terms of performance and implementation. In this chapter, to achieve the objectives of a modular design approach, good voltage regulation and good load sharing, a novel droop method using a gain-scheduling technique is proposed.

The merits of the master/slave scheme are stiff voltage regulation and precise load sharing. However, the limitations are also obvious. The implementation of the scheme relies on interconnected circuitry between the two converters. The converters are usually controlled dependently. Therefore, not only is it undesirable for modular design, but the overall system reliability is also reduced because of the additional interconnection.

A typical control structure for a single boost rectifier is shown in Figure 6.1. The output DC voltage loop is superimposed on the d-channel current loop. The q-channel current reference is set to zero in order to have a unity power factor operation. H_{id} and H_{iq} are current compensators for d and q channels, respectively. H_v is output voltage compensator.

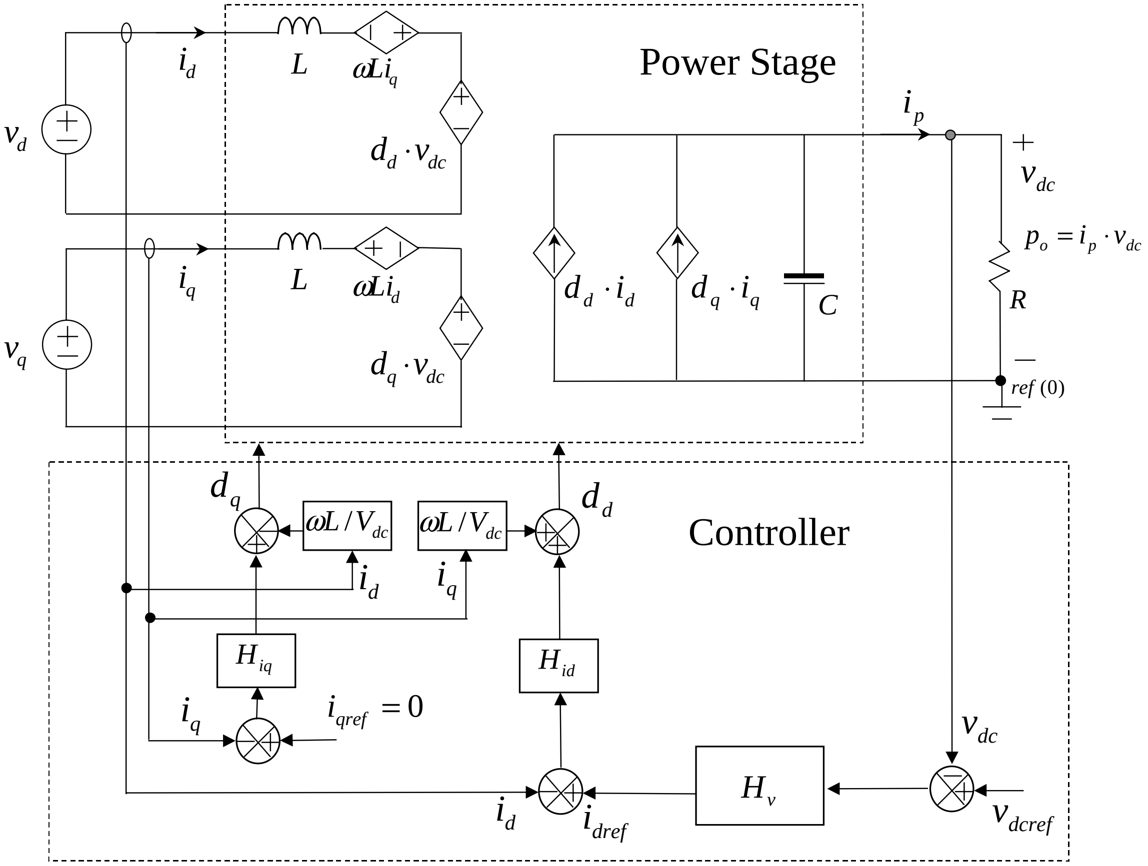


Figure 6.1 Control structure of three-phase boost rectifier.

The voltage compensator usually has an integrator in order to have a zero steady-state error; as an example, a typical compensator is shown in Equation (6.1).

$$H_v = \frac{K \cdot (s/z+1)}{s \cdot (s/p_1+1) \cdot (s/p_2+1)}. \tag{6.1}$$

When two converters with the same control design are in parallel, both of them regulate voltage precisely because the integrator provides an infinite DC gain. As a consequence, the load sharing relies on load distribution due to the effect of the bus cable impedance [63].

One solution is to loosen the stiff voltage regulation in order to obtain a droop characteristic. The voltage compensator H_v uses a finite DC gain, that is, without the integrator, as shown in Equation (6.2):

$$H_v = \frac{K_v \cdot (s/z+1)}{(s/p_1+1) \cdot (s/p_2+1)}, \tag{6.2}$$

where p_1 is a dominant pole of the loop gain in order to have an appropriate margin. As a result, a droop characteristic is obtained, as shown in Figure 6.2. The slope of the droop curve is proportional to the DC gain K_v. Based on the droop characteristic, the power can be controlled within a certain range by controlling the voltage within specific intervals. Both converters can be controlled independently and the objective of modular design can be achieved.

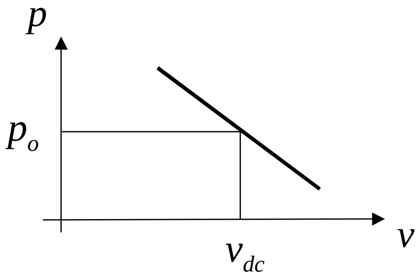


Figure 6.2 Droop characteristic.

However, the droop method has a fundamental limitation in that good voltage regulation and good load sharing cannot be achieved simultaneously. Figure 6.3 shows that good voltage regulation requires a high DC gain, while a high DC gain could cause poor load sharing if the two converters are not identical. The curves with good voltage regulation cause a large power imbalance if there is even a small variation in their droop characteristics, while the curves with good load sharing have large voltage variation (a dashed line is a variation of a solid line).

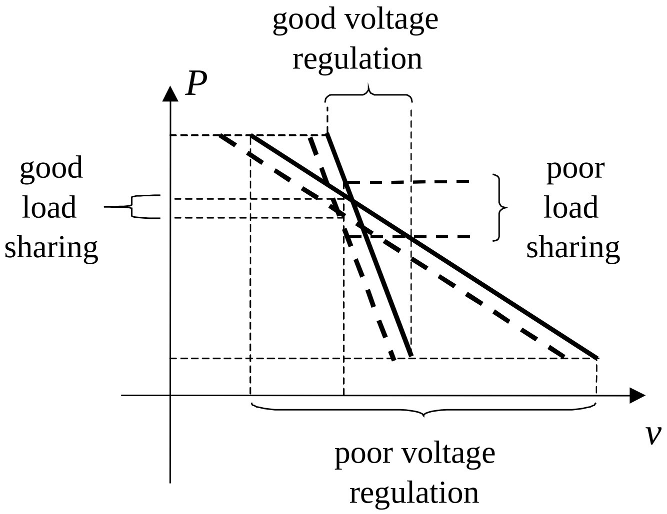


Figure 6.3 Limitations of droop method.

In the next section, a novel droop method using gain scheduling is proposed in order to improve both voltage regulation and load sharing. Not only does the proposed method maintain modularity, but it also has better performance than the droop method.

6.2 A NOVEL DROOP METHOD USING GAIN-SCHEDULING TECHNIQUE

6.2.1 Parametric Analysis

Designing the droop method with gain scheduling involves the analysis of three parameters of a single converter: voltage compensation DC gain K_v, steady-state output DC voltage V_{dc} and output power P_o, as shown in Figure 6.1.

The output power P_o may change from light to heavy load in normal operation. Figure 6.4 shows that the output voltage V_{dc} is a function of both the DC gain K_v and the output power P_o. The voltage and the power are normalized to their nominal values. It can be seen from Figure 6.4 that, the voltage V_{dc} increases nonlinearly as the gain K_v increases. With a constant gain K_v =2, that is, with the design of a normal droop method using the compensator in (6.2), the voltage variation from light to heavy load is 4%, as shown with dotted lines in Figure 6.4. To reduce the voltage variation, the gain K_v has to increase. However, in order to maintain the stability margin, the position of the dominant pole p_1 in (6.2) has to be at a lower frequency when the gain gets higher. Therefore, the gain K_v is limited by the closed-loop dynamic requirement.

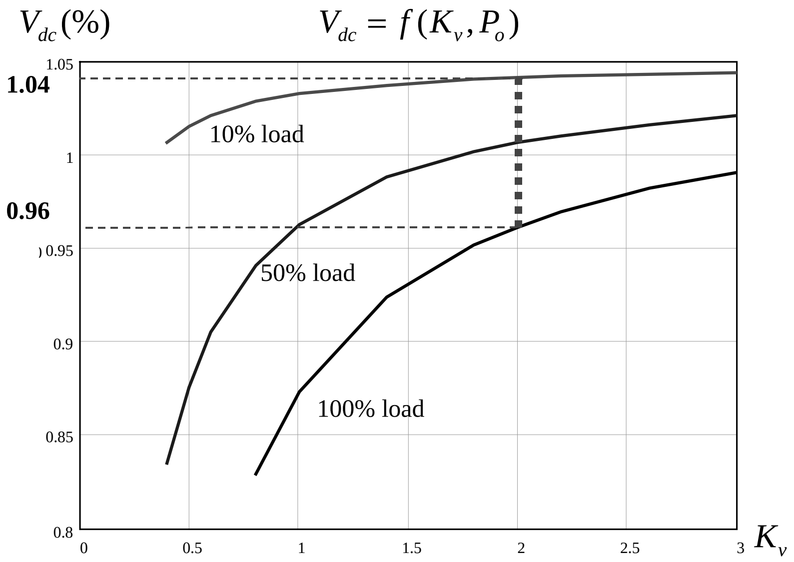
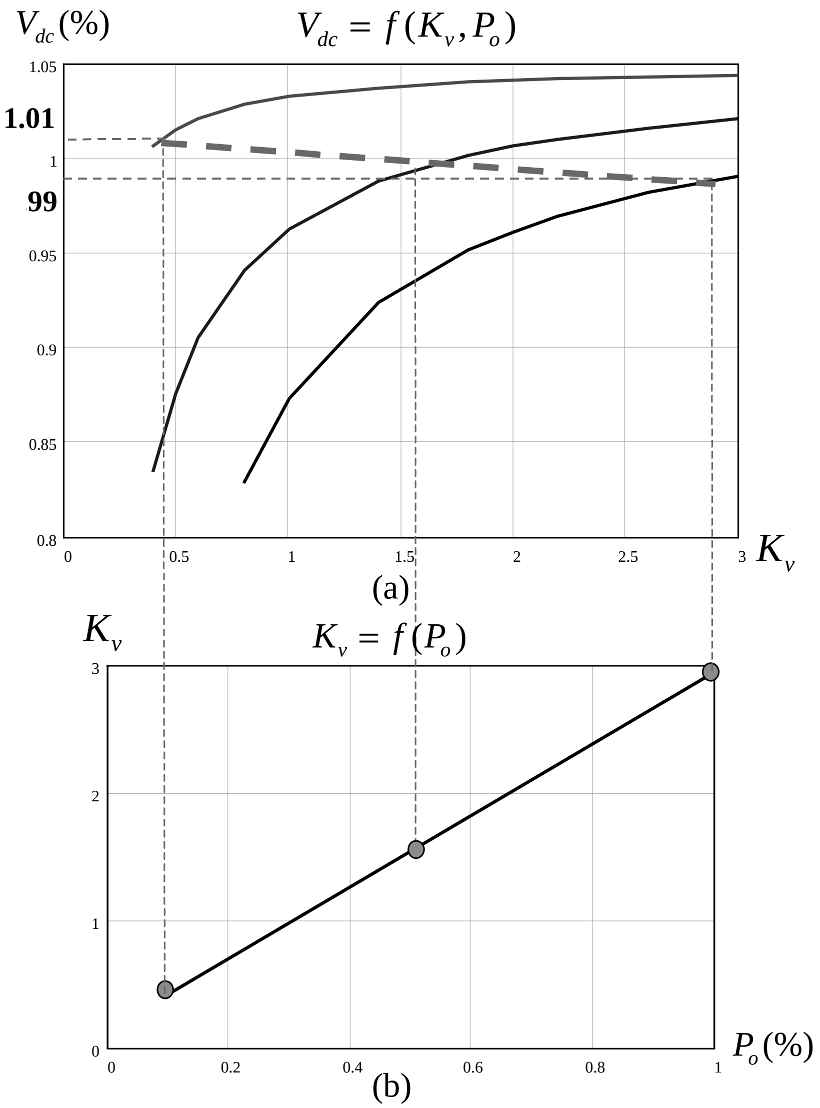


Figure 6.4 Output voltage is a function of DC gain and output power.

6.2.2 Gain-Scheduling Curve

One way to limit the voltage variation is to change the gain K_v dynamically. For instance, under a 1% voltage variation, the gain should be controlled in the range shown with a dashed line in Figure 6.5(a). The gain change corresponds to changes in output power so that the voltage variation can be controlled within a desired range. To obtain the relationship between the gain and the power under the 1% output voltage variation, the dashed line in Figure 6.5(a) is projected onto Figure 6.5(b) with the K_v-P_o axes. As a result, a gain-scheduling curve is obtained. The gain-scheduling curve indicates that, if the gain K_v follows this curve when the load power P_o varies, the voltage V_{dc} can be controlled within 1% as desired.



(a)

(b)

Figure 6.5 Gain-scheduling curve.

Based on this idea, the voltage loop is modified, as shown in Figure 6.6. A gain-scheduling loop is incorporated into the original voltage loop by multiplying the varying gain that depends on the output power. Because the gain-scheduling loop introduces additional nonlinear dynamics to the system, a low-pass filter is necessary to minimize the nonlinear effect [64], [65].

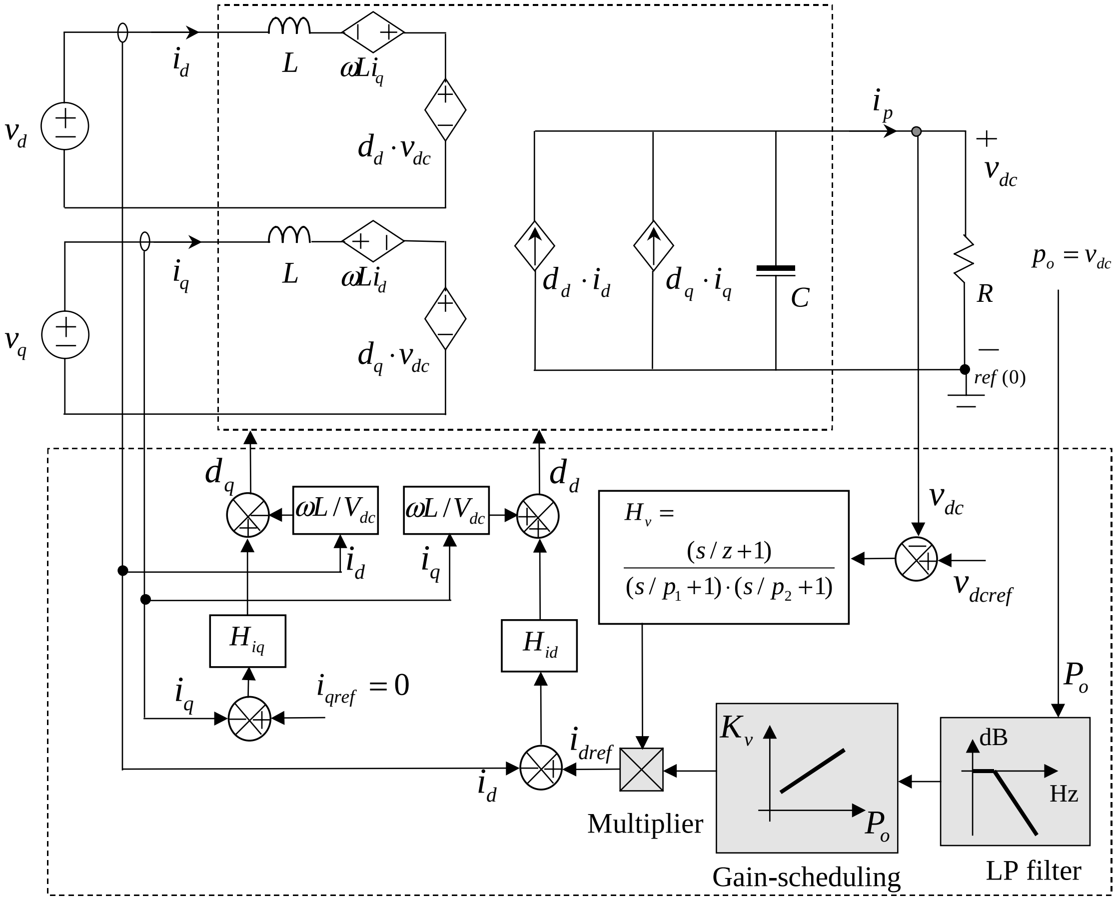


Figure 6.6 Control modification in a single converter.

Based on this idea, the parallel converters can be designed individually with their own current and voltage loops. The simulations described in the following section demonstrate the performance of the new design. The following simulation results were obtained using two parallel three-phase boost rectifiers. Their parameters are shown below:

$V_{rms(a,b,c)} = 120\,\text{V}$; $\omega = 2\pi \cdot 60\,\text{rad/s}$; $V_{dc} = 400\,\text{V}$; $P_o = 15\text{kW}$ (full power); $L_1 = 200\mu\text{H}$; $ESR_{L_1} = 20m\Omega$ $C_1 = 1000\mu\text{F}$, $L_2 = 300\mu\text{H}$; $ESR_{L_2} = 50m\Omega$ $C_2 = 1300\mu\text{F}$, $H_{id1,2} = \frac{-2}{2\pi \cdot 160} + \frac{-2}{s}$, $H_{iq1,2} = \frac{-2}{2\pi \cdot 160} + \frac{-2}{s}$, $H_{v1,2} = \frac{(s/2\pi \cdot 50 + 1)}{(s/2\pi \cdot 10k + 1)}$, Gain-scheduling loop low-pass filter: $LP_{1,2} = \frac{1}{(s/2\pi \cdot 100 + 1)}$.

6.2.3 Simulation Results

The objective of a modular design is achieved through the droop concept, and the objective of good voltage regulation is achieved by using the gain-scheduling technique. The effect of the gain scheduling on the load sharing still needs to be investigated. Three schemes were compared in terms of transient response and load sharing. They are:

(a) Both converters use a constant gain (K_v =2) with 4% voltage variation,

(b) Both converters use a constant gain (K_v =7) with 1% voltage variation, and

(c) Both converters use the gain scheduling (K_v =0.5~3) with 1% voltage variation.

Figure 6.7 shows their droop characteristics: schemes (a) and (b) are straight lines with different slopes because of their different gains, and thus different voltage variations; scheme (c) is a nonlinear curve with the same voltage variation as in scheme (b).

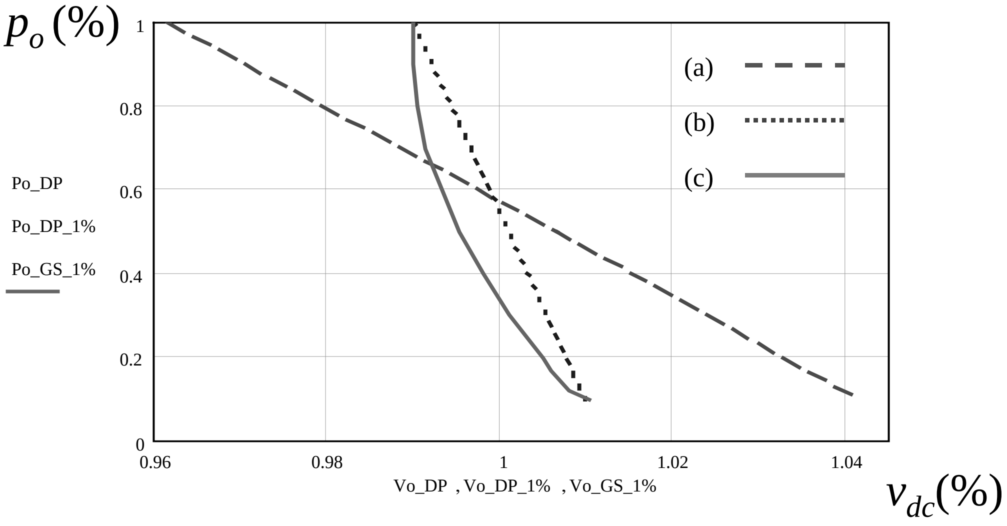
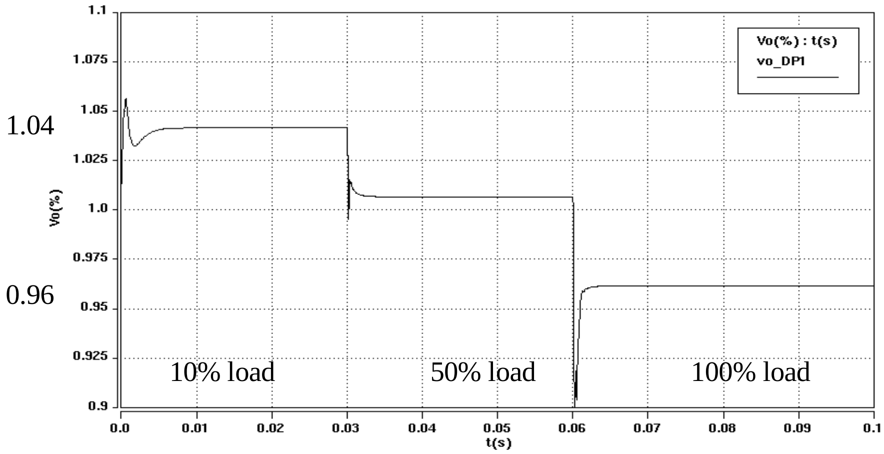
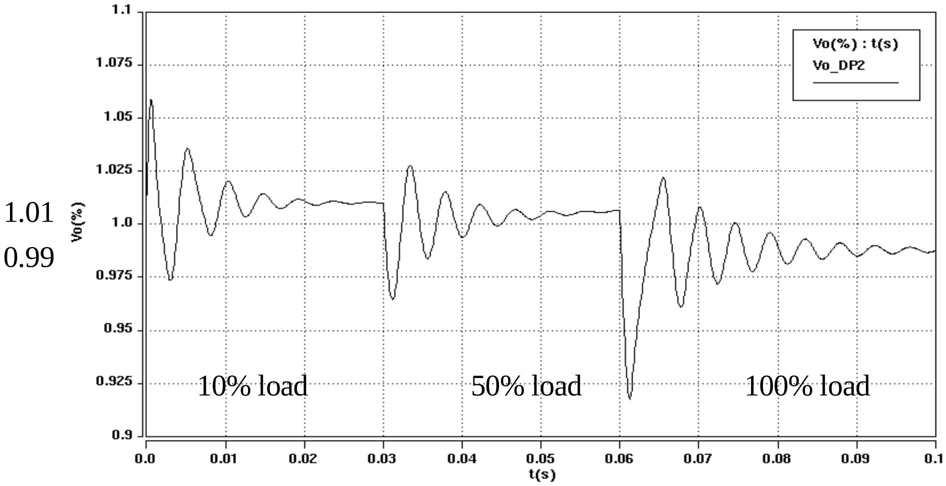


Figure 6.7 Droop characteristics of three schemes.

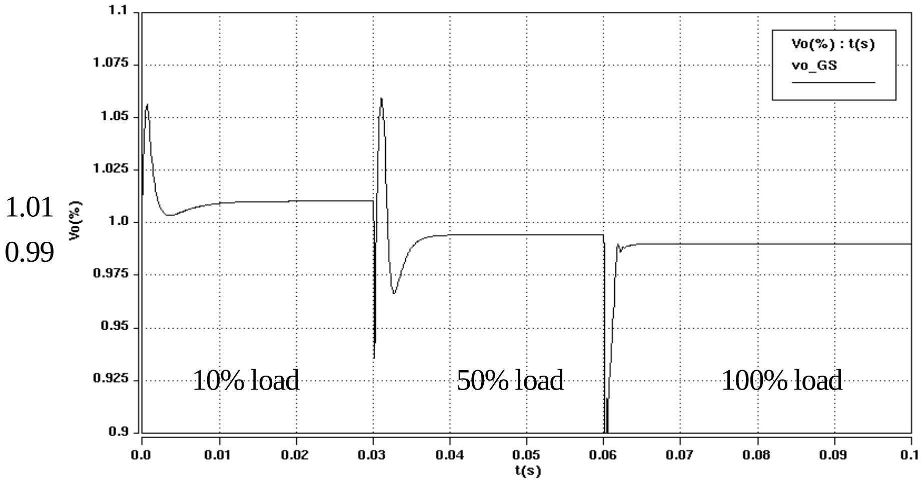
Although gain scheduling imposes additional dynamics on the system, it does not change the dynamic of the original voltage loop very much because of the low-pass filter. Therefore, the voltage transient response is almost the same as that of scheme (a), shown in Figure 6.8. Due to its low-frequency dominant pole, scheme (b) has a much slower transient response, as shown in Fig 6.8(b).



(a) Scheme (a).



(b) Scheme (b).



(c) Scheme (c).

Figure 6.8 DC bus voltage with different schemes.

Figure 6.9 shows the three schemes' load-sharing performance when the boost inductors of one module are 5% larger than the other ones. Because of the mismatch between the two modules, the load sharing has a certain percentage difference due to the modules' non-identical droop characteristics. Scheme (c) is not as good as scheme (a), but is better than scheme (b), because the effective gain of scheme (c) is smaller than that of scheme (b). The curves in Figure 6.10 show that the droop method with a constant gain cannot achieve both good voltage regulation and good load sharing. Scheme (b) has lower voltage variation than scheme (a), but has a larger imbalance of load sharing as well as slower response. With gain scheduling, scheme (c) has the same voltage variation as scheme (b), but has better load-sharing performance. In other words, scheme (a) has poor voltage regulation but good load sharing, scheme (b) has good voltage regulation but poor load sharing, and scheme (c) has good voltage regulation and fair load sharing.

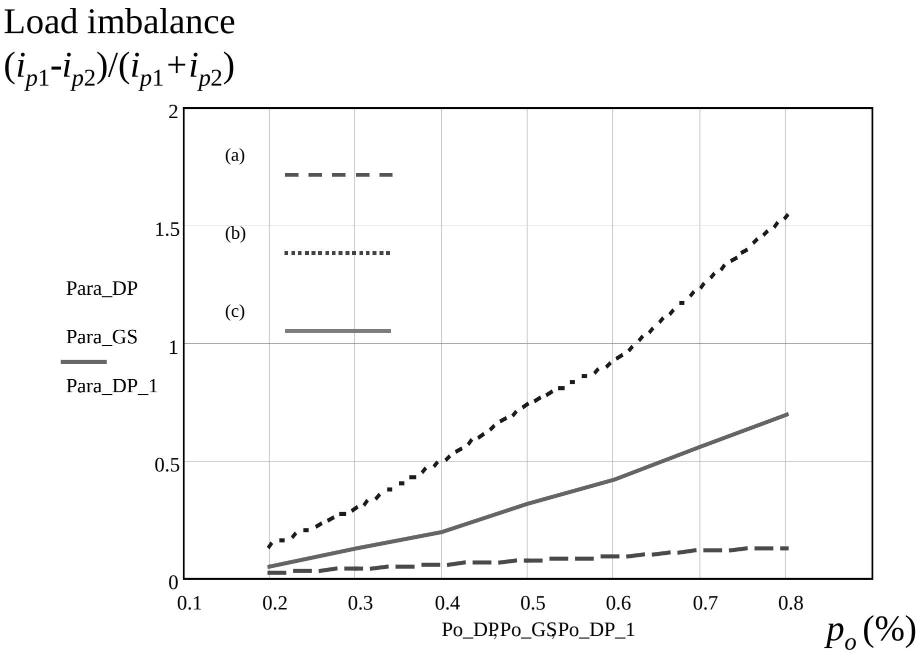


Figure 6.9 Load sharing performance with different schemes.

As a result, the objective of modular design is achieved using the droop concept, voltage regulation is achieved using the gain-scheduling technique, and load sharing is maintained at an acceptable level.