Application of Adaptive Droop Method to Boost Converters Operating at the Output of Fuel Cells

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Abstract

Droop method is widely used to operate dc-dc converters in parallel. Although it is very simple and easy to use, poor regulation and uneven load sharing are the major limitations of the method. This paper presents a modified droop method to overcome these limitations. Proposed method is an adaptive technique that re-defines the droop coefficients after an initial period of operation. The method has been tested with three boost converters designed to operate at the output of a fuel cell. Results clearly show that better regulation and load sharing are achieved using the suggested technique.

1. Introduction

Using lower rated converters in parallel instead of a single, larger rated converter offers several advantages such as higher efficiency, better dynamic response, better load regulation, higher reliability, ease of maintenance, and smaller size energy storage devices [1]. Current or load sharing is the most critical parameter in parallel operation of converters. Most of the methods to guarantee equal load sharing utilize some form of communication between the units. This increases the complexity and sensitivity to noise. Systems without communication line may use various control algorithms. Injection of an ac signal proportional with the output current into the power line is one method investigated in [2-4]. This actually means that the communication is done through power line. The disadvantages of these systems are the control complexity, application difficulty and RF noise generation possibility due to the interference of various frequencies at the output.

The most reliable method without communication line is the droop method [5-11]. However, this method has some limitations. The most serious limitation comes from the fact that the output voltage needs to be reduced significantly to achieve an acceptable level of power sharing as the difference between the set values of the output voltage of each converter increases. This means that the droop method is not a good alternative if a good load voltage regulation is required. A possible solution to this problem is to adjust the voltage droop (gain scheduling) when the load varies [10,11]. This may be a good solution if the system is operating near the rated power. However, a current sharing with a good voltage regulation may not be obtained under all load conditions. The method suggested in [11] is proper for all load conditions. However, in this method, rated power level should be reached at least once for a good current sharing. Thus, it is not proper if the rated power is not required by the load for a long time

A new droop method is suggested in this paper. Proposed method employs an adaptive algorithm to determine the droop coefficient. A droop coefficient is calculated when the system is first started and after certain time it is modified. As a result of this algorithm better voltage regulation and current sharing are achieved compared to classical droop method. This technique relies on a single bit synchronization line which is used only during start-up.

Proposed technique has been tested on a three-unit boost converter system used at the output of a fuel cell. Experimental results show that the proposed method has a better load regulation and load sharing.

2. Droop Method

Droop method is widely preferred for parallel operation of converters mainly due to its simplicity. However, the biggest drawback of this method is the poor voltage regulation. As the current or power sharing is improved the voltage drop increases.

Recently, the authors suggested a modification on the application of the droop method [12]. The suggestion is to aim for input power sharing rather than output power or current. Although the technique remains the same, this modification is advantageous especially when the input source has limited power. Renewable energy sources can be considered in this category.

Figure 1 shows the concept of droop method for three-converter case, when the input power sharing is aimed.

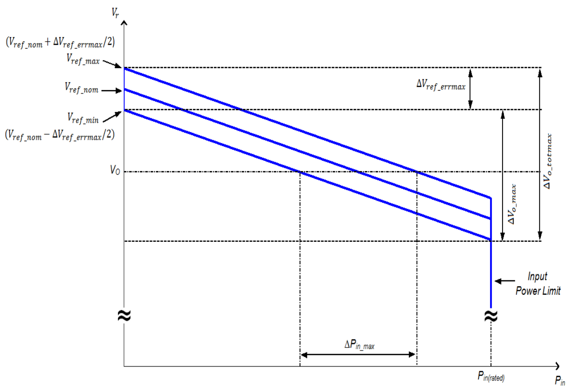

Fig. 1. Droop characteristics for three-converter case

Equation (1) shows the power sharing and voltage drop relationship adapted to input-power sharing system.

$$\frac{P_{in(rated)}}{\Delta P_{in\_max}} = \frac{\Delta V_{O\_totmax}}{\Delta V_{O\_seterrmax}} - 1 \qquad (1)$$

where ΔP_{in_max} is the maximum value of the differences between the unit power values, ΔV_{o_totmax} is maximum value of the voltage drop, and $\Delta V_{o\_seterrmax}$ is the maximum value of differences between the set values of the converters. These parameters can also be visualized by the help of Figure 1. Figure 2, shows the voltage drop versus power mismatch variation obtained from (1).

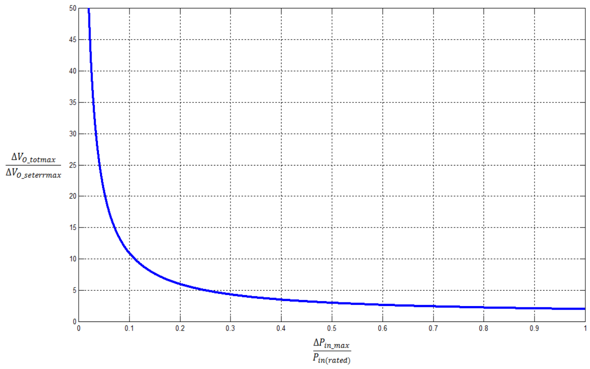

Figure 2. Voltage drop versus power mismatch for droop method

In order to prove the concept described in this paper, a system consisting of three 100 W converters has been designed to boost 24 V dc to 48 V dc. It is well known that due to practical limitations, reference values of each converter always deviate from what they should be. It is assumed that maximum difference between the output voltage reference (V_{ref}) values is 100 mV, and individual references are as follows: 48.05 V, 48.00 V, and 47.95V. If it is desired that 1.25 W (1.25%) power mismatch is accepted for this system ($\Delta V_{o\_seterrmax}$=100 mV), then the voltage drop is found to be 8.1 V which means a voltage regulation of 16.8%. This is not a preferable operation condition.

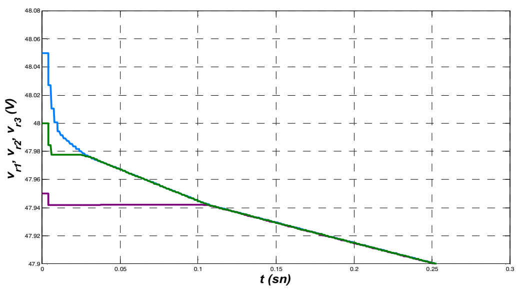

Figure 3. Operation of droop method for a load of 37.5 W

The droop coefficient for this is system is calculated to be b=0.08. For a stable system it is desired that tracking should not be very fast. Figure 3 shows the simulation result for a load power of 37.5 W. The system is started with this load, and it takes about 100 ms for the reference voltage of the converter with the highest set point (48.05 V) to catch up with the converter having the lowest set point (47.95 V.) At this instant converters start sharing the current (Figure 4). Almost equal current sharing is achieved around 120 ms at which time the output voltage is 47.94 V.

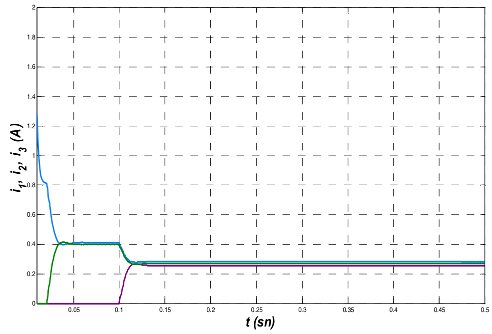

Figure 4. Current sharing of the converters with the droop method working on the example system loaded at 37.5 W.

2.1. Proposed Method

As mentioned above, droop characteristics are tracked with a time constant, and as a result of this, especially at high power levels, power sharing is realized before the rated load is undertaken. At light loads, power sharing process is slower, but by increasing the droop slope it can be made faster.

Figure 5 shows the classical droop method when the system is loaded with full load. As seen from the figure it takes about 100 ms to achieve sharing at full load.

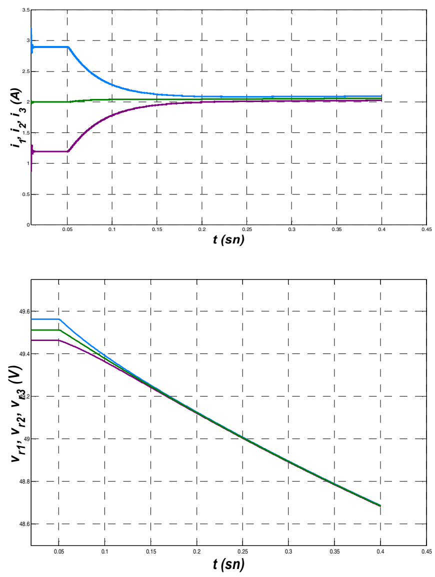

Figure 5. Classical droop method at full load (300 W): Unit current variations (top) and voltage references (bottom)

Proposed method is based on variable droop coefficient constant. When the load power is low, a higher droop coefficient can be used to achieve power sharing at a short time just like high power case. In the adaptive droop method proposed here all the converters start tracking the droop characteristics at the same time and for all load conditions, tracking is ended at the same specific time. Any possible errors at the end point can be eliminated by using another droop coefficient which depends on the initial coefficient.

Adaptive droop method needs to use a synchronization information. This makes it possible for each converter to start tracking the droop characteristics at the same time and to start the sharing. The synchronization is achieved by a one-bit connection. Therefore, no communication algorithm is required, and synchronization interconnection is not needed after the power sharing is achieved. Even when the whole system is shut down and restarted again, output voltage references of each converter start from where the power sharing is achieved last. A microprocessor can be used to achieve this feature.

When the synchronization bit is received by the controller a droop coefficient in inverse proportion with the power level at that instant is determined, and tracking starts. The coefficient reaches its steady state value after a while. Figure 6 shows the algorithm that determines the droop coefficient and tracks the droop characteristic. Figure 7 shows the complete block diagram of the method, and Figure 8 gives the algorithm flow chart.

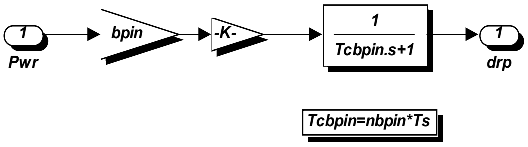

Figure 6. First order droop slope controller

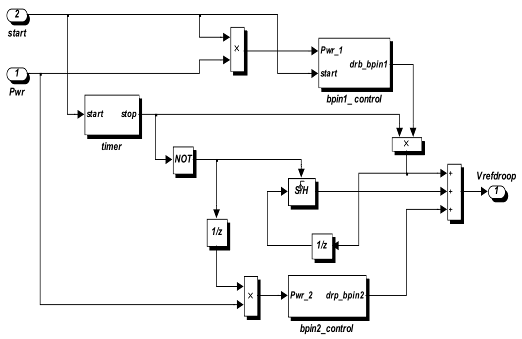

Figure 7. General block diagram for adaptive droop method

3. Experimental Results

Three boost converters have been designed to operate from the output of a Ballard Nexa 1.2kW fuel cell. Fuel cell output varies between 48 V (at no load) and 24 V (at full load.) Boost converters boost the output voltage to 48 V, and each is rated 100 W.

In the first set of experiments a three-step loading was used. Initially the system is at no-load. After some time load is switched to half-load, and then to full-load. Later, the load is removed in the reverse sequence. This sequence is first applied when classical droop method is running, and then when no sharing algorithm is in use, and eventually when the proposed method is run. Figure 9 and 10 show the results. In Figure 9, adaptation is implemented at half load, while it is implemented at full load in Figure 10.

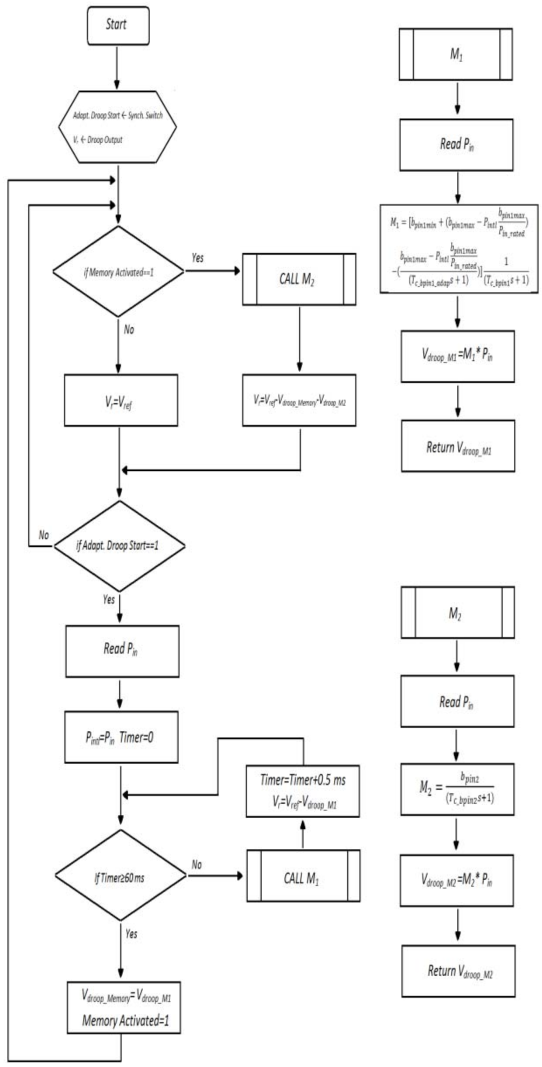

Figure 8. Flow chart of the adaptive droop method

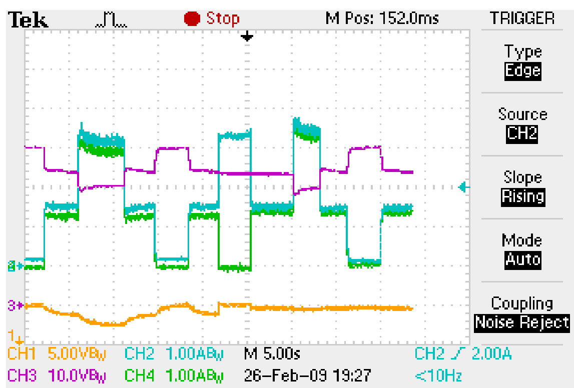

Figure 9. Three-step loading experimental results (adaptation at half-load): input currents (CH2,CH4), fuel cell voltage (CH3), and load voltage (CH1).

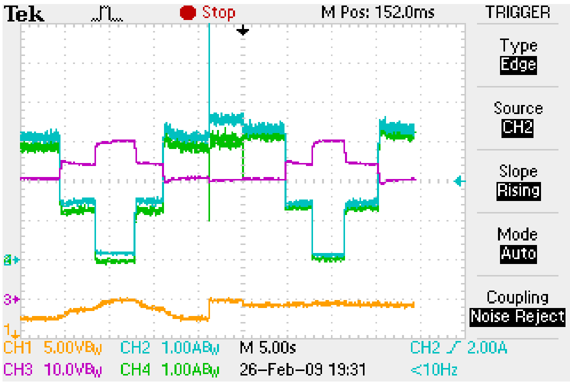

Figure 10. Three-step loading experimental results (adaptation at full-load): input currents (CH2,CH4), fuel cell voltage (CH3), and load voltage (CH1).

Following observations can be made by investigating the figures:

- Fuel cell voltage drops dramatically as the load increases. The voltage drop is about 10 V for 300 W load.
- When no sharing algorithm is in use (middle part of the three-step loading) voltage drop of the converter output is not much, but there is a big current mismatch between the units (as much as 800 mA.)
- When classical droop method is in use (the first part of the three-step loading) output voltage of the converters drop dramatically (around 2.8 V at full load). Current mismatch is also poor (around 350-400 mA at full load).
- When the proposed adaptive method is applied, the voltage drop is only 850 mV at full load. Meanwhile, power mismatch is also reduced dramatically with the proposed method (around 200 mA.)

Figure 11 and 12 show the response of the converters to load change for the two methods. Response with the classical method is seen in Figure 11 while the response with the proposed method is shown in Figure 12. In these experiments, the converters are initially at no load, and the it is suddenly switched to full load.

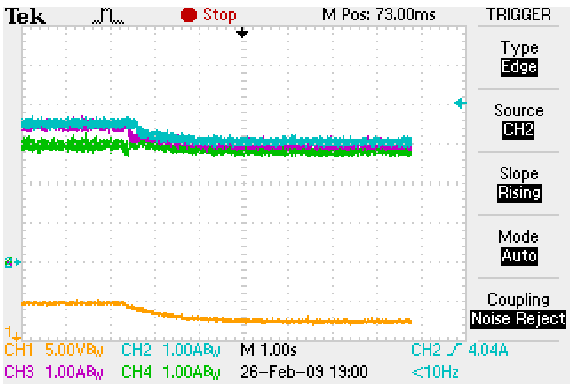

Figure 11. Response to step load change (no load to full load) with classical droop method: input currents (CH2,CH3, CH4), load voltage (CH1)

When the two responses are compared, it can be concluded that the classical droop method has a smoother response. However, adaptive droop method yields better voltage regulation (around 850 mV, compared to 2.5V of the classical droop) with a better current sharing (around 100 mA compared to 200 mA of classical droop method.)

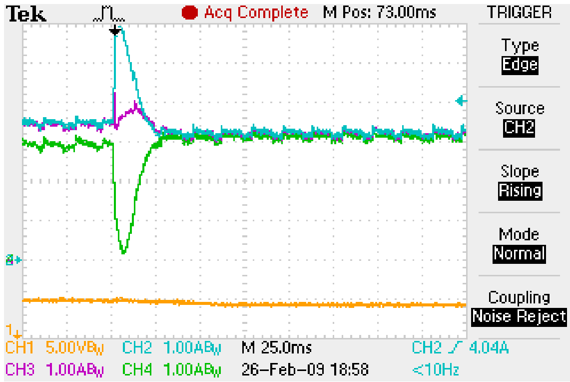

Figure 12. Response to step load change (no load to full load) with the proposed adaptive droop method: input currents (CH2,CH3, CH4), load voltage (CH1)

6. Conclusions

Droop method is widely used in parallel operation of dc-dc converters due to its simplicity. However, load voltage regulation is poor, and power sharing between the units are not good. A new droop method which yields much better voltage regulation and power sharing is proposed here. The method adaptively changes the droop coefficients of the converters a certain time after the start-up. Once this is done, the converters use the same coefficients whenever they are restarted. A single-bit synchronization line is needed for this operation. This line is used only at the start-up and not needed afterwards.

Proposed method is tested over three boost converters designed to operate at the output of a fuel cell. Since output power of renewable energy sources are limited, input power sharing of the converters instead of the output is more important. Therefore, the method is applied to the converter inputs. Results show that better voltage regulation and power sharing are achieved with the suggested technique.

7. Acknowledgment

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8. References

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