Non-Droop Methods for Context-Sensitive Sharing in Multi-Module Switching Converters

Philip T. Krein
Dept. of Electrical & Computer Engineering
University of Illinois
at Urbana-Champaign, USA

Jonathan W. Kimball
Electrical & Computer Engineering Dept.
Missouri University of Science and Tech.
Rolla, Missouri USA

Brian T. Kuhn
SmartSpark Energy Systems
Champaign, Illinois USA

Abstract -- **This paper introduces automatic methods that support intentional nonuniform power or current sharing in multi-module dc-dc converter configurations. Sharing that is proportional to ratings or to external weighting values is supported. The methods extend to input-series output-parallel and input-parallel output-series connections as well as to conventional parallel-parallel configurations.**

I. Introduction

Modular power converters in parallel or mixed parallel-series configurations, including input-parallel output-parallel (IPOP), input-series output-parallel (ISOP), input-parallel output-series (IPOS), and input-series output-series (ISOS) connections, are usually controlled for matched power sharing. Uneven sharing has generated some recent interest. One example combines a fast module with low power ratings and slow modules with high power ratings for dynamic performance [1]. Combinations in which one regulation stage is combined with multiple unregulated stages have also been proposed [2, 3]. More comprehensive gradient-type combinations, in which multiple converters with stepped ratings support wide load ranges, are described in [9, 10]. The emphasis there is on the nonuniform architecture rather than the control: although uneven sharing is intended, there is little discussion in [10] on how it would be achieved.

More generally, uneven sharing has a number of possible applications:

1. Sleep modes in which the low-power mode is a small fraction of rated load, such that a single low-power module should carry sleep-level load. Similarly, stepped loads linked to stepped converters, as in [10], are relevant.
2 Expandable or integrated systems in which converters with disparate ratings can be interconnected.
3. Alternative energy resource configurations in which wind, solar, or other resources that are stochastic and variable in power level are to be interconnected.
4. Hybrid energy storage systems that combine batteries in a range of ratings with ultracapacitors, fuel cells, or other devices.
5. Microgrids that combine many sources and loads while seeking cohesive controls.
6. Combinations in which modules differ in power ratings, dynamic capability, or other factors that impact sharing during either transient or steady-state conditions.

In some of these applications, notably microgrids [4], conventional frequency droop or voltage droop controls support context-sensitive sharing. Droop gains can be set readily to achieve uneven power sharing proportional to unit ratings or other factors.

The objective of this paper is to elucidate non-droop approaches that support context-sensitive sharing in various modular converter connections. The non-droop approaches provided here support intentional uneven sharing that can be designed to achieve the objectives associated with the listed applications. The most basic approach shares power in proportion to module ratings automatically. More comprehensive approaches allow a user to preset arbitrary sharing fractions.

II. Set Point Uneven Sharing

Consider the ISOP connection shown in Fig. 1 – a four-phase bidirectional modular configuration based on push-pull dc-dc modules. It has been established that open-loop sensorless current mode (SCM) control [5] will produce "super-matched" power sharing since the input currents must match and the output voltages also must match [6]. In fact, the underlying mechanism is that SCM control operates each converter based on an input voltage V_{in}/n, which has the effect of matching duty ratios. As it turns out, SCM does not cause stability problems, and each phase will provide an uneven fraction of the total power if the effective control voltage has a weight other than $1/n$. The same strategy applies directly to the IPOS connection: set up the SCM control for a given converter i as a weighted fraction w_i of the total input voltage.

Provided that the sum of all weights is unity, $\sum_i w_i = 1$, in the ISOP connection, an SCM-based control law will deliver the desired output voltage while drawing different fractional power from each converter. In this connection, the input voltages will not match, but instead will track the weighting value for each module. Since the input currents must match in the ISOP connection, this simple strategy provides proportional power delivery. The IPOS connection is just the dual: in this case, the weighting factor is applied to the desired output voltage, while all input voltages match. The result will be proportional output voltage fractions, and, consequently, proportional input current fractions. In the

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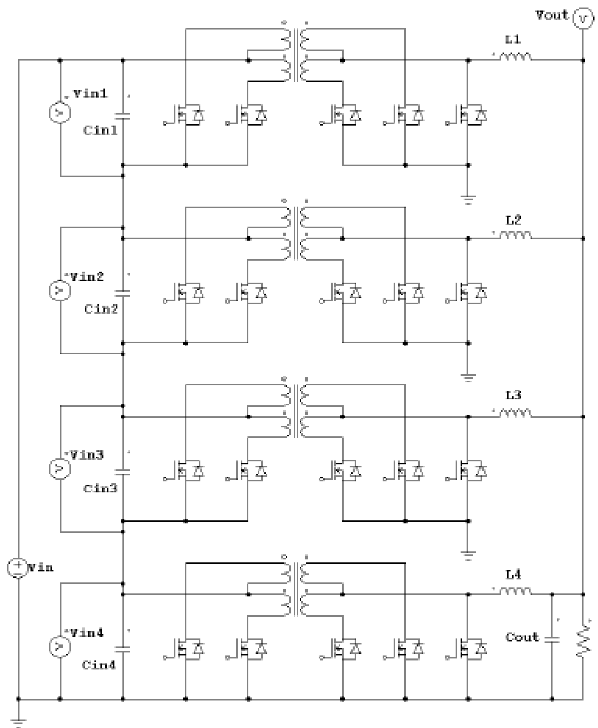

Fig. 1. ISOP converter configuration example.

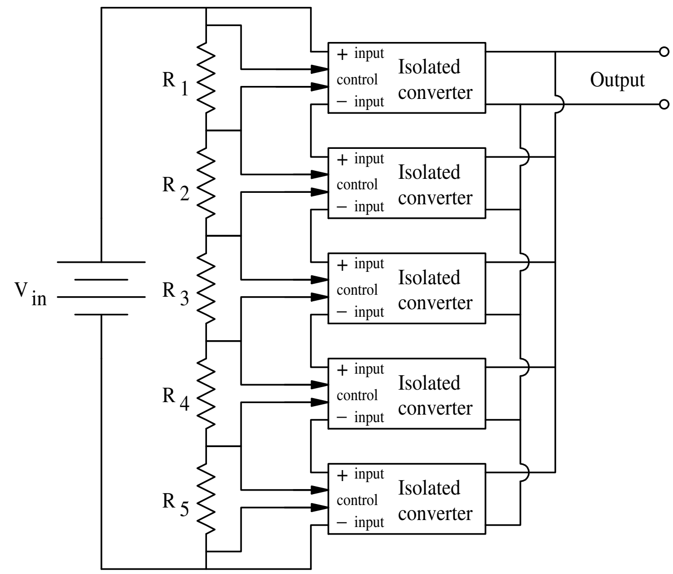

Fig. 2. ISOP configuration with potential uneven sharing. Each converter is controlled to have a fractional portion of the input, based on the corresponding resistor value.

IPOP configuration, the approach resembles the controls of [7, 8], in which nonidentical converters are controlled for uniform current sharing. In [8], weights are mentioned, although the emphasis does not seem to include intentional non-uniform sharing. A challenge in all such cases is that the weights must be predetermined, and the approach does not seem to lend itself to simple expandability.

This approach, which can be termed "set point sharing," can be adapted to avoid the challenge of weights and expansion through a simple expedient. If a set of weighting resistors associated with each individual module is used to construct a divider, the total voltage across the divider will be 100%. The weights associated with each module will be proportional to its associated resistor, e.g. a module with double the weight resistor of another will be set to double the voltage (and power) of the other.

A set point automatic sharing action is represented in Fig. 2, in which a high-impedance "sharing bus" (a voltage divider in the ISOP and IPOS connections) serves to provide individual reference values on the series side of the connection. In the ISOP case, each individual converter sees the fraction of V_{in} determined by the divider. The sum of all voltages is automatically 100% of V_{in}, and the divider resistances become weight. In this configuration, it is easy to envision how a system can be expanded by inserting an additional module, packaged with its divider resistor, into the series string. In a standardized system, the resistor could be proportional to module power rating to make the sharing follow the same proportions as the power ratings.

Set point sharing is easy enough in both voltage-mode and current-mode multi-module applications. In a current-mode application, the total current to be supplied under current-mode control can be converted to a proportional voltage and divided in a weighted manner among modules, just as in Fig. 2. Notice that in this case there is also a possibility of dynamic weighting. Since the converter control input is taken as a high-impedance point, careful use of parallel capacitors across the weighting resistors will govern sharing behavior during certain types of fast transients. Under a fast line transient, modules with larger weighting capacitors would be slower to respond to the change. Fast load transients, in contrast, are linked to values of power stage input capacitances shown in Fig. 1: the larger a given input capacitance, the more the associated module will deliver short-term transient power.

III. Source-Effect Sharing

Dynamic effects on transient sharing governed by energy storage elements in weighting and input circuits suggest another uneven sharing alternative. If the input capacitances represent real sources, for example, sharing will be governed by dynamic behavior of individual sources.

Fig. 3 shows an independent multi-module case, such as might be considered for a microgrid, intended for source-effect uneven sharing. As a simple example, consider the case in which all batteries in Fig. 3 have the same nominal voltage but have different amp-hour storage ratings. The high-impedance sharing resistor set generates a single-wire sharing bus that provides each converter with an average voltage representative of all inputs. Each converter will deplete its own battery in proportion to its relative power delivery. The SCM process in Fig. 3 guarantees that if an individual battery begins to lose voltage, the current will drop since the duty ratio for the overworked converter will be too low for full power delivery. The actual power drain from each module will automatically follow the local capability of its battery. In some sense, this resembles a droop control, and details depend on static and dynamic impedance characteristics as well as energy capacity of each unit. But there is no droop gain or true droop control involved – the action is passive, just as if series resistance had been added at each input. In practice, the high effective gain of the SCM approach will drive the desired ratings-proportional sharing with minimal actual voltage droop. Other control techniques that incorporate input voltage feedforward, where the true input voltage is replaced by the shared control voltage, would similarly result in ratings-proportional sharing. The principle of ratings-based sharing based on source effects thus is established. This arrangement has important possibilities in that it permits easy interconnection of unequal power sources in a manner that will track relative ratings.

An interesting effect of Fig. 3 is automatic ratings-based sharing: the modules will share current in proportion to the source power ratings, provided the source impedance behavior is monotonic with ratings. A similar effect can be observed in alternative energy systems or in ultracapacitor-based storage systems: sharing will be nonuniform in proportion to either resource generation or individual module input capacitor value for modular systems of this type. Fig. 4 shows a self-contained remote power unit that implements the circuit of Fig. 3, except that the dc sources represent internal energy storage rather than input photovoltaic power. The unit in Fig. 4 is designed to deliver up to 5 W-h/day under low sun conditions. Two identical units connected as in Fig. 3 yield a direct doubling in capability, with even sharing. A larger unit, with storage rated to support 25 W-h/day, can be connected with the small unit shown to produce a 30 W-h/day system that shares unevenly – 1/6 of the power coming from the small unit and 5/6 from the larger one.

Fig. 5 shows an uneven sharing example based on source effects. Three converters, of the same general type as in Fig. 4, are being applied in a parallel combination. Each converter has a different rating, reflecting the internal energy storage capacity. When the control is started about 8 ms, the currents separate in proportion to the ratings. The center trace, the output voltage, is fixed. The other three traces are the currents.

IV. Discussion

Uneven sharing in various multi-module distributed power configurations, with its wide range of potential applications, can be supported with set point and source-effect approaches. In current-mode controls, uneven current set points can be created. In voltage-mode controls, sensorless current mode control approaches provide

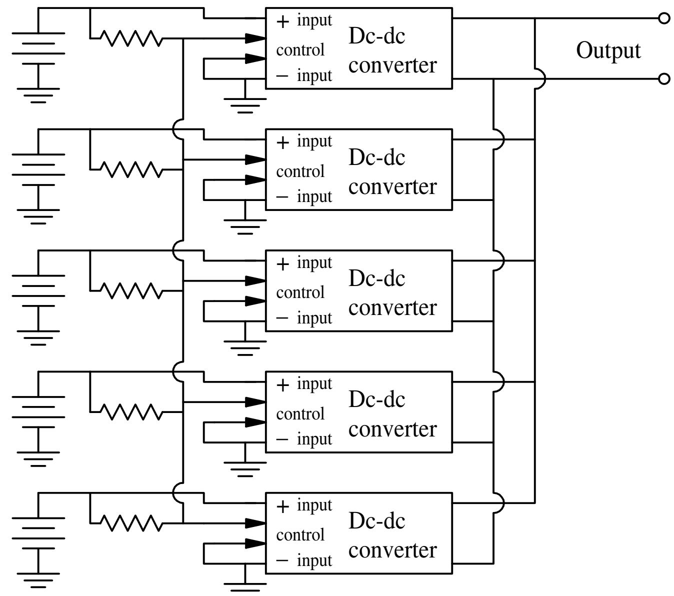

Fig. 3. Multi-module system with resistive sharing bus. Current will divide automatically in proportion to source conductance or power capability.

convenient ways to set up nonuniform current sharing. Methods have been introduced that share power based on predetermined internal weighting resistances or that share

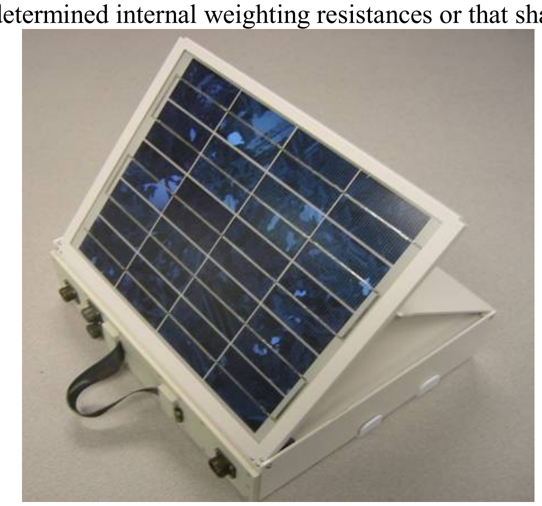

Fig. 4. Remote power unit designed for uneven sharing interconnection. This unit is rated to deliver 5 W-h/day under poor conditions.

power in proportion to ratings with no further intervention. Sharing methods that produce context-sensitive nonuniform sharing, such as current sharing in proportion to ratings, or power sharing in proportion to resource availability are possible.

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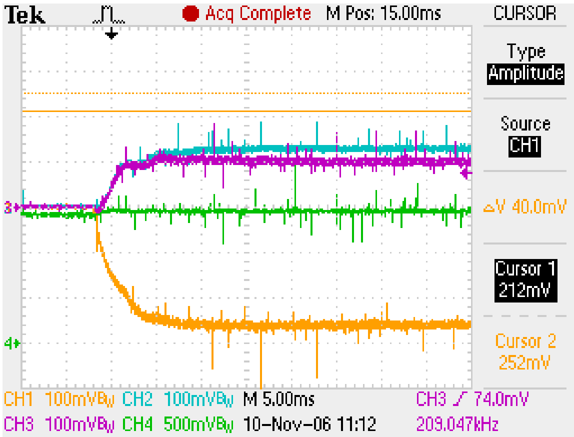

Fig. 5. Currents under source-based sharing for three parallel converters.

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