Classification of Parallel DC/DC Converters Part I: Circuit Theory

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***Abstract*— This paper describes a classification of paralleling schemes for dc/dc converters from a circuit theoretic viewpoint. The purpose is to provide a systematic classification of the types of parallel converters that can clearly identify all possible structures and control configurations, allowing simple and direct comparison of the characteristics and limitations of different paralleling schemes. In the proposed classification, converters are modeled as current sources or voltage sources, and their connection possibilities are categorized systematically into three basic types. Moreover, control arrangements are classified according to the presence of current-sharing and voltage-regulation loops. Comparison is presented to illustrate the characteristics of the various schemes.**

I. Introduction

Paralleling of standard dc/dc converters has been widely adopted in distributed power systems for both front-end and load converters. One basic objective of parallel-connected converters is to share the load current among the constituent converters. To do this, some form of control has to be used to equalize the currents in the individual converters. A variety of approaches, with varying complexity and current-sharing performance, have been proposed in the past two decades [1]. In general, methods for paralleling dc/dc converters are described in terms of connection styles, control configurations and feedback functions. Although some forms of classifications and comparisons have been given for paralleling schemes [1]–[2], most fall short of a systematic identification of all possible structures and control configurations.

In order to facilitate design and choice of appropriate paralleling configurations, a systematic classification of the paralleling schemes that permits a clear exposure of the structures, behaviors and limitations of all possible schemes, is needed. In this paper, we investigate the classification problem and utilize basic circuit theory to identify the basic structures and control methods of parallel dc/dc converters. Our objective is to provide a simple classification that eliminates redundancy, includes all possible basic structures, permits comparative analysis of different structures, and hence allows systematic derivation of paralleling schemes.

Our starting point will be the two Kirchhoff's laws that dictate the possible connection styles. Considering converters as either voltage sources or current sources, we define three basic structures for paralleling converters. As we will see, these structures actually form the basis of all practical paralleling schemes. We will develop equivalent models which can be used in analysis. Furthermore, control methods will be systematically introduced to complete the output regulation and current-sharing functions. Finally, a general comparison of various configurations will be presented.

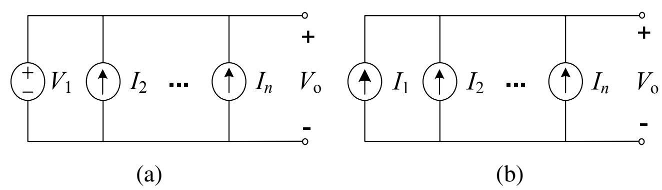

Fig. 1. Structures for paralleling ideal independent sources.

II. Basic Circuit Theory of Parallel Connections

A. Basic Constraints in Paralleling Independent Sources

Two basic laws must be obeyed when connecting sources together. First, Kirchhoff's voltage law (KVL) dictates that no two independent voltage sources are permitted to be connected in parallel. Theoretically, even if the voltage sources are of the same magnitude, paralleling them is still not permitted as it violates KVL and makes the current values undefined [3]. Likewise, Kirchhoff's current law (KCL) eliminates the possibility of connecting two independent current sources in series. In this paper, as our focus is paralleling sources, we do not consider the case of connecting sources in series.

From the above discussion, it is clear that independent sources can be connected in parallel under only two possible circumstances, as shown in Fig. 1. First, only one of them can be an independent voltage source, and the rest must be current sources, as shown in Fig. 1 (a). The output voltage is decided by the voltage source branch, and the current in the voltage source is determined by the load. Second, all parallel branches are current sources, as shown in Fig. 1 (b). The output voltage is decided by the load.

It should be clear that in practice, the voltage and current sources are not independent but are controlled sources in order to allow regulated output voltage and specific sharing of current to be maintained. Nonetheless, the aforementioned two basic configurations will form the basis of parallel connection styles. The applications of these connection styles and the associated control problem will be the main subjects of discussion of this paper.

B. Equivalent Circuits for DC/DC Power Converters

Dc/dc converters are devices for processing power. For most practical purposes, a regulated output voltage or current is

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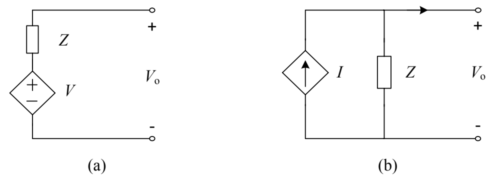

Fig. 2. Equivalent circuits for power converters. (a) Thévenin form; (b) Norton form.

required of a converter, mandating the use of some feedback control to keep the converter unaffected by load and input disturbances. As a result, a dc/dc converter can be viewed as an imperfect voltage or current source with appropriate control of its magnitude in response to output and/or input variations. In general, we may simply and generically represent a dc/dc converter in Thévenin form or Norton form, i.e., a dependent voltage behind a small impedance (at low frequency) or a dependent current source in parallel with a large impedance (at low frequency), as shown in Fig. 2.[1] Theoretically, the two representations are arbitrary. However, it should be clear that the Thévenin form is more suited for converters whose purpose is to achieve a regulated output voltage, whereas the Norton form is suited for converters whose purpose is to achieve a regulated output current. Obviously, voltage feedback is needed for the former case, and current feedback for the latter.

III. General Classification of Parallel Connected DC/DC Converters

From the foregoing discussion, it is clear that any paralleling scheme involving voltage and current sources must comply with the two basic structures described earlier. Moreover, if the voltage sources are imperfect,[2] they can still be connected in parallel. Thus, we have three basic configurations for paralleling imperfect sources.

When dc/dc converters are treated as imperfect voltage or current sources, three basic configurations for paralleling practical dc/dc converters can be developed, as summarized in Fig. 3. For brevity, we refer to these configurations as Types I, II and III connections. For a voltage source branch, we have

$$V_o = V_i - I_{o,i}Z_i \quad \text{or} \quad I_{o,i} = \frac{V_i - V_o}{Z_i} \tag{1}$$

where subscript i (1 to n) indicates the branch number, and $I_{o,i}$ is the output current of the ith branch, i.e., the part of load current shared by the ith branch. For a current source branch, we have

$$V_o = (I_i - I_{o,i})Z_i \quad \text{or} \quad I_{o,i} = I_i - \frac{V_o}{Z_i} \tag{2}$$

where I_i is the equivalent current source of the ith branch.

In practice, we need to apply appropriate control to dc/dc converters in order to "cast" them as voltage or current sources. For instance, a voltage feedback loop is obviously needed for controlling a dc/dc converter so that it behaves as a voltage source. Thus, the paralleling configurations are closely related to the control method which effectively determines whether a dc/dc converter would behave as a voltage or current source.

In addition to the defining control of current and voltage sources, a current sharing control can be used to ensure even sharing of the load among the converters. To avoid confusion, we will use the term *current-sharing loop* in a specific context. If a current sharing control signal is derived from the output currents of one/all constituent converters, the control scheme is said to contain a *current-sharing loop*. Otherwise, the control scheme does not have a current-sharing loop.

We may therefore further classify parallel converter systems according to the presence of a current-sharing loop, resulting in a simple, systematic classification, as shown in Fig. 4. Two layers are included in the classification. In the first layer, we get three configurations, Types I, II and III, based on the circuit theoretic connection styles. In the second layer, the presence of a *current-sharing loop* is the classifying criterion.

IV. Three Types of Connection Styles and Associated Control Methods

In this section, in light of the classification framework mentioned in the foregoing, the various types of parallel connected dc/dc converters are described in detail. Our emphases here are the generic circuit theoretic structures and the necessary control methods. As a prerequisite, we note that converters aiming to imitate voltage sources should have tight voltage feedback loops for voltage regulation purposes, whereas converters imitating current sources would necessitate some form of current-mode control in order to set the current magnitudes. The presence of current-sharing loop is an additional feature, contributing to the current sharing of the constituent converters.

A. *Type I*

The Type I connection is shown in Fig. 3 (a). Each branch represents a converter, which is basically a Thévevin source. For the control without current-sharing loop, the branches are simply connected in parallel. No other extra action is taken among the converters to achieve current balance. However, the absence of a current-sharing loop imposes some specific requirements on the individual branches in order to provide natural current sharing. This has been commonly known as the *droop method* [1]. Specifically, each converter, in the absence of a current-sharing loop, should have a finite output resistance at steady state, which results in obvious droop characteristic of the converter. Otherwise, any small discrepancy of V_i and/or Z_i will cause severe current imbalance among the converters.

For Type I connection with current-sharing loop, since all converters are Thévenin sources, output regulation and current sharing are achieved by controlling $V_1, V_2, \cdots, V_n$ and/or the output impedance $Z_1, Z_2, \cdots, Z_n$. The control structure is shown in Fig. 5. In this configuration, each converter is a dependant voltage source, whose output voltage is controlled directly. The currents sensed from different converters are

[1]By "small" impedance and "large" impedance, we actually refer to the modulus of the impedance.

[2]By imperfect sources, we mean those voltage sources having non-zero output impedance and those current sources having finite output impedance.

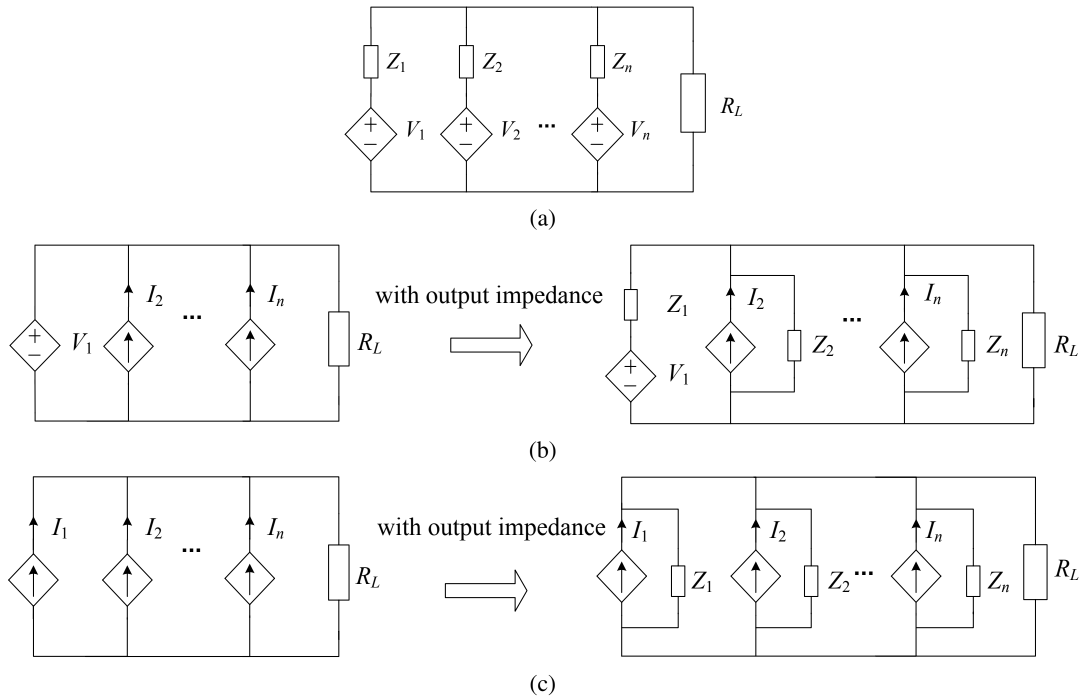

Fig. 3. Three configurations for paralleling converters. (a) Type I; (b) Type II, with practical form on the right; (c) Type III, with practical form on the right.

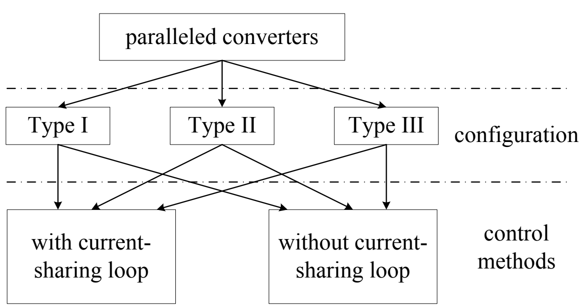

Fig. 4. A systematic classification of parallel connected converters.

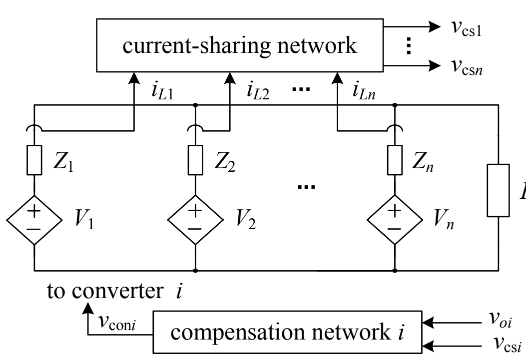

Fig. 5. Control structure for Type I configuration with current-sharing loop.

programmed to obtain a common current sharing control signal, which will be compared with the feedback currents to regulate individual equivalent voltages $V_1, V_2, \cdots, V_n$. The objective is to shrink the discrepancy of the converters. Thus, all converters share the load equally.

B. Type II

For the Type II connection shown in Fig. 3 (b), one converter serves as the voltage (Thévenin) source and others are current (Norton) sources. The control structure without current-sharing loop is shown in Fig. 6 (a). There is a main voltage feedback loop, which acts on the voltage (Thévenin) source to regulate the output voltage. Other branches are under current-mode control (peak-current-mode control is applied in the paper), whose objective is to make all individual output currents share the same portion of the load current.

For the Type II configuration with current-sharing loop, the control structure is shown in Fig. 6 (b). Again, there is a main voltage loop to control the voltage source. The current control signal for the current sources will be derived from the voltage source branch. This current control signal is then compared with the individual current of the $N-1$ converters to achieve current sharing. This method is commonly known as *master-slave current-sharing method* [1], where the voltage source is the master and the current sources are the slaves whose currents are programmed to follow the master's.

C. Type III

In the Type III configuration shown in Fig. 3 (c), all converters are current (Norton) sources. In the absence of a current-sharing loop, all converters have to follow a current sharing control signal which is derived from the output voltage feedback loop, as shown in Fig. 7 (a). The feedback loop aims to achieve voltage regulation as well as current-sharing. A simple implementation can be found in Iu *et al.* [4].

Finally, for the Type III configuration with current-sharing loop, all converters are under current-mode control so that

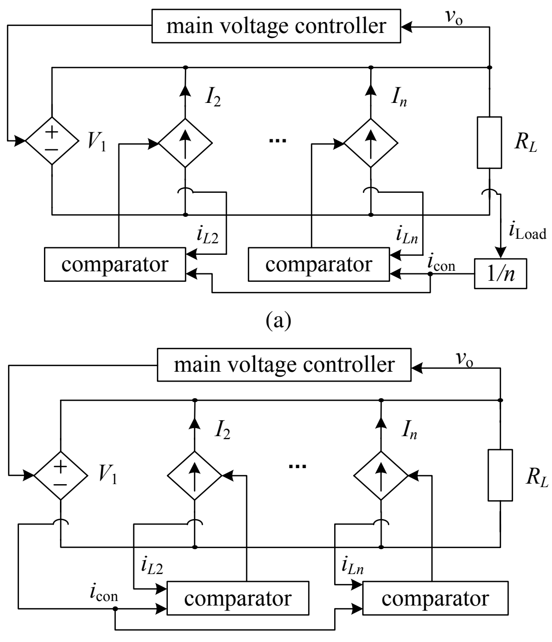

Fig. 6. Control structures for Type II configuration (a) without current-sharing loop; (b) with current-sharing loop (also known as master-slave current-sharing).

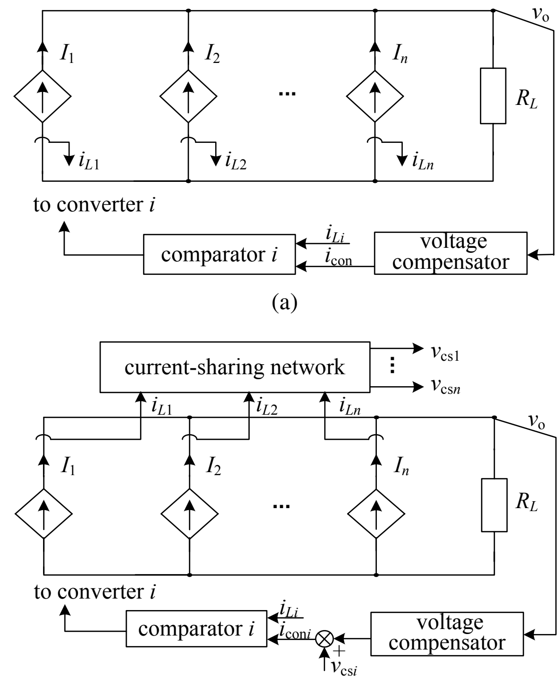

Fig. 7. Control structures for Type III configuration (a) without current-sharing loop; (b) with current-sharing loop (also known as democratic current-sharing).

they behave as good current sources. Current-programming methods, such as master-slave method or average method, can be used to generate the common current-sharing control signal. The amplified errors between the current sharing control signal and the feedback currents are injected to the feedback loop as shown in Fig. 7 (b).

V. Comparison of Paralleling Schemes

In the foregoing section, we have discussed the structures and the associated control methods for paralleling dc/dc converters. Intuitively, we can make the following general observations. Detailed analysis will be presented in a companion paper [5].

1) Type I schemes are simple but suffer fundamentally from paralleling voltage sources. The adjustment range for current sharing is small since each constituent converter is designed primarily to regulate its output voltage.
2) Type II schemes are theoretically more viable as there is only one voltage source paralleling with current sources. The dynamics of the voltage regulation thus depends on the control method being employed by the voltage regulating loop. The other current source converters control their currents directly to achieve the desired current sharing. Thus, the current-sharing performance is generally much better and the control implementation is simpler, compared to Type I schemes.
3) Type III schemes are generally best in terms of current sharing as all converters are fundamentally current controlled. The voltage regulation is only executed at the load side.

VI. Conclusions

In this paper, a systematic classification of parallel connected switching power converters is given. Our starting point is circuit theory of connecting voltage and current sources as converters can be regarded as voltage or current sources. Three basic types of paralleling schemes can be identified, corresponding to (i) connecting Thévenin sources in parallel, (ii) connecting one Thévenin source with many Norton sources in parallel, and (iii) connecting Norton sources in parallel. The presence of current-sharing loop has been considered as an optional feature, though its use has been clearly proven to be important for achieving good performance in current balancing. The classification presented in this paper allows the paralleling schemes to be systematically analyzed. A detailed comparison of the performances will be presented in a companion which has been submitted to this conference [5].

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