Digital Control of Parallel-Connected DC-DC Converters

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***Abstract*—This paper presents a digitally-controlled paralleled DC-DC converter. The main objective of the digital control is to achieve load sharing while operating at close to peak efficiency over an extremely wide load range. Results from computer simulations using Simulink show the digital control could indeed accomplish the objectives, but the improvements over a single converter depend on the original efficiency characteristics of the converters. An application for a high-power electric vehicle charger utilizing this converter setup is considered.**

I. Introduction

There exist several advantages to parallel-connected DC-DC converters, including increased reliability, decreased stress on critical components, improved efficiency, and more flexibility [1,2]. In distributed power systems, parallel-connected converters have been in use for many years [2]. In the emerging market of electric vehicles, there arises the need for high-power chargers which are reliable, cost effective, and very efficient [3]. These chargers most often use a constant-current constant-voltage charging scheme, in which the current is first very high, and by the end of the charge it is much lower [4]. Because of this, a charger with high efficiency across a wide load range meets the need of today's advanced systems. It is widely known that paralleling converters when carefully designed may accommodate the load sharing capability required by the high current applications. However, a conventional controller which incorporates load sharing at any load level suffers the drawback of poor converter's efficiency especially at low output current. Hence, a more advanced or smarter controller will be needed to manage the number of converters in parallel required based on the load current which in turn will keep the efficiency of the converter relatively high.

In this paper, a digital controller that senses and determines the number of paralleled converters per given load current will be discussed. The controller model using Simulink was developed and explained in this paper which provides a tool for investigating the effectiveness of paralleled DC-DC converters, and allows easy development of a digital control scheme. One simple control scheme is simulated, and compared to a control case of a single converter. Finally, paralleled converters are considered for use in high-power electric vehicle chargers.

II. Simulink Model Development

In papers such as [5] and [6], mathematical models are developed for building a Simulink model of a DC-DC converter. The approach taken in this paper is somewhat different. Instead of modeling the converter directly, a model is developed using only efficiency characteristics of a given DC-DC converter. This way, the model can be applied to any converter topology and to any number of different converters within a single topology. The converter is modeled as an efficiency lookup table, with inputs of load current and a control signal to enable or disable each converter. The outputs of the converter are input and output power as well as efficiency. Fig. 1 shows this model with inputs and outputs labeled. An accompanying MATLAB file can be modified to update the lookup table values, as well as the V_o value.

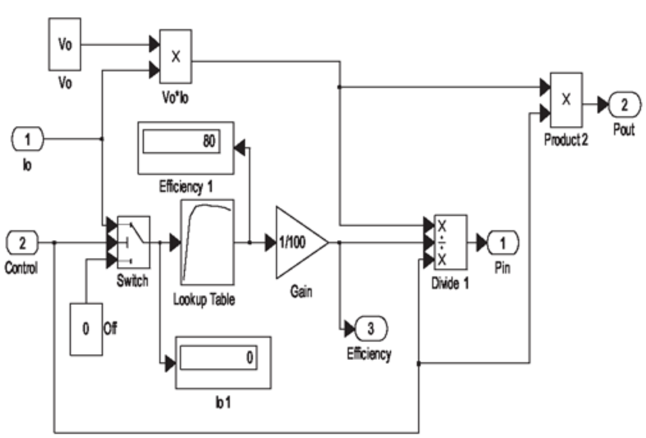

Figure 1. DC-DC converter efficiency model.

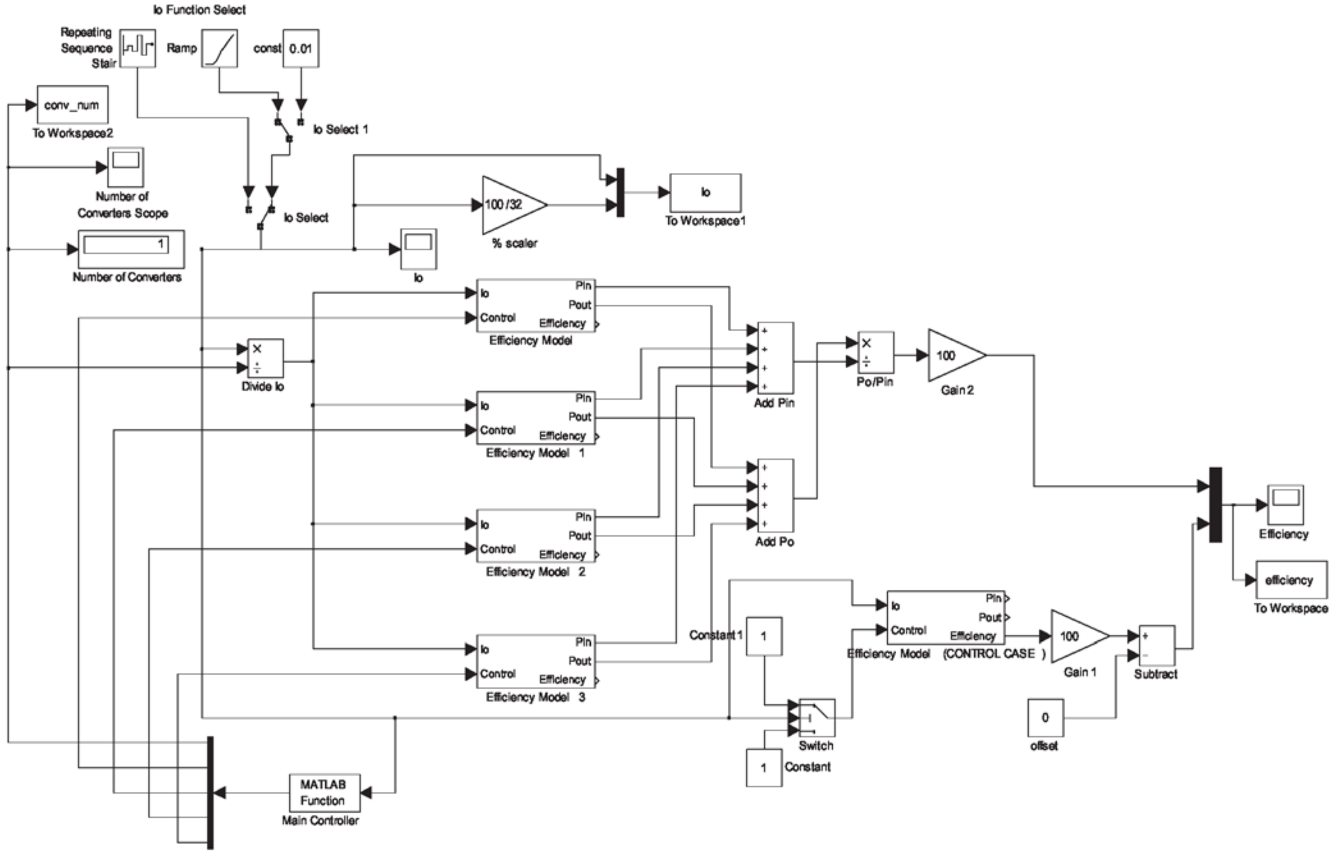

Figure 2. Complete parallel-connected DC-DC converter Simulink model.

The efficiency model was then integrated into a parallel-connected DC-DC converter setup, as shown in Fig. 2. In this complete model, total combined output current is divided by the number of active converters (discussed in more detail in the controller section below). This divided output current then feeds into the individual efficiency blocks to determine the efficiency of the system. At the output of the efficiency model blocks, the input and output powers are summed and then divided to give a total efficiency for the complete system. Any converter not enabled does not contribute to these total powers. A control case efficiency model is also fed by the total output current, and provides a comparison between the paralleled system and an equivalent stand-alone converter. The main controller block shown in Figure 2 runs a MATLAB function during runtime which acts as the digital controller of the system. This controller has the ability to enable or disable individual converters.

III. CONTROLLER

The controller in this model is implemented via a MATLAB function and included in the model shown in Fig. 2. The present controller is fairly rudimentary, and was written to show the general functionality of the system as a whole. In future work, a much more sophisticated controller will be developed.

To test the validity of the model, example efficiency and load limit values were loaded into the controller. The controller functions by first looking at a table of efficiencies at various loads, and finding the peak efficiency and the corresponding load current. This load current $_{(Imax)}$ becomes the current limit at which DC-DC converters are enable or disabled, depending on the total load. As an example, if there are a total of four parallel converters, then the total allowable load current is $4I_{max}$. With four converters, there are four switch points. If the total load current is below $_{Imax,}$ then only one converter is enabled. If the current is between $_{Imax}$ ^{and} $_{2Imax,}$ then two converters are brought online, and so on.

This control scheme does not employ a master-slave type configuration as discussed in [7] and [8], but rather allows any converter to be enabled individually while the others are disabled. This will allow future development advantages such as thermal stress management. This means that future digital control schemes will look at converter temperature, and depending on the number of parallel converters enabled, will dynamically swap out converters that are running hot (due to long run times or environmental conditions). This adds an added level of control and robustness to the parallel-connected system.

IV. RESULTS AND DISCUSSION

Using the controller and Simulink model discussed above, some simulations were performed to verify the improved efficiency of the parallel-connected DC-DC converter over the single converter. For the converter efficiency characteristics, an example curve was obtained from a Texas Instruments synchronous Buck battery charge-controller chip, the bq24620 [9]. Fig. 3 shows the sample efficiency curve used in the simulation. Similarly, the curve was modified for the case of the single converter. In this instance, the same efficiency values were used but the load currents were multiplied by 4 (to give a range of 0A to 32A). Also, an output voltage of 48 volts was chosen to give the total system a power rating of 1.54 kW (each individual converter then was 384 W). For the output current, a ramp function was chosen with an initial value of 0A and a final value of 32A.

Using these parameters, the simulation was run and efficiency plots were generated. Also, the number of enabled converters was captured. Fig. 4, the efficiency for the parallel-connected converter is shown along with the control case of the single converter. Here it can be observed that for loads over 28% full load, the converters have the same efficiency. Below 28% load, the parallel-connected converter maintains a high efficiency, all the way down to below 4% load. With a more sophisticated control algorithm, this low-end efficiency could be brought up even more. Also with a more sophisticated control algorithm, the jagged low-end efficiency could be smoothed out. This test was also performed using efficiency data from a converter with a flatter efficiency cure to start with. In this case, the paralleled-converter did not perform as desirably, and did not show the low-end gains.

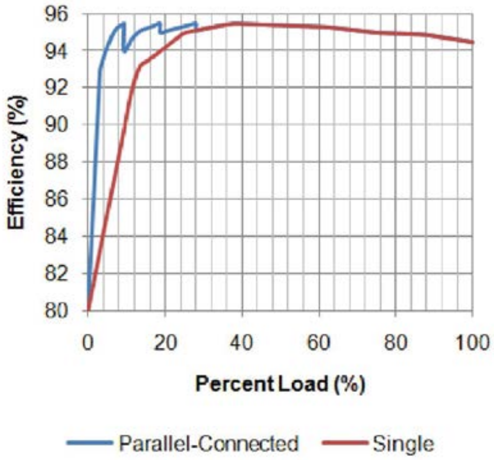

Figure 4. Efficiency vs. percent load for parallel-connected converter as compared to the control case of a single converter.

Figure 3. Sample efficiency curved used for individual DC-DC converter characteristics in simulation.

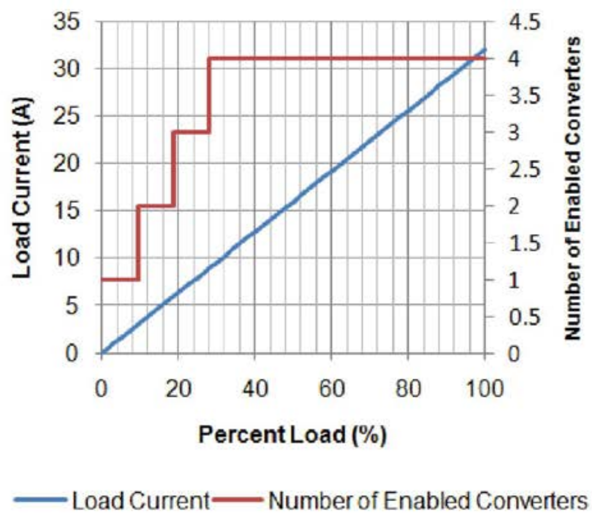

Figure 5. Load current and number of enabled converters.

Fig. 5 shows the input load current and the number of enabled converters for the simulation. As described earlier, the load current ramps up from 0A to 32A. The number of enabled converters increases as expected as the load current increases. As the load current passes integer multiples of $_{Imax,}$ successive parallel converters are enabled, up to the maximum (four in this case).

A second simulation was performed using the efficiency characteristics shown in Fig. 6. This efficiency curve does not sag off at higher loads, but decreases more at lower loads. Fig. 7 shows the results of the second simulation using the efficiency characteristics of Fig. 6. In this case, the efficiency at 8% full load shows a 12% improvement of the parallel-connected converter over the single converter. The parallel-connected converter maintains a minimum efficiency of 94% from 8% full load to 100% full load. Finally, a third simulation was performed using a converter with a flatter efficiency curve, shown in Fig. 9. Fig. 10 and Fig. 11 show the resulting efficiency curves and number of enabled converters. In this case there is not as much of a percentage in efficiency gain at the low-end load as compared to the second simulation, but never-the-less some gains are made.

Finally, a third simulation was performed using a converter with a flatter efficiency curve, shown in Fig. 9. Fig. 10 and Fig. 11 show the resulting efficiency curves and number of enabled converters. In this case there is not as much of a percentage in efficiency gain at the low-end load as compared to the second simulation, but never-theless some gains are made.

V. APPLICATION EXAMPLE

One application that would appear to benefit from such a load sharing scheme is the fast-growing technology of high-power battery chargers for electric vehicles. As previously discussed, these chargers have a wide load requirement and need to be efficient over that load range. A parallel-connected DC-DC converter topology such as the one presented in this paper would serve this purpose, also allowing for smaller, cheaper power components, and providing peak efficiency for the majority of the charge. In [10] and [11] the constant-current constant-voltage (CCCV) charge algorithm is discussed, and the tapering current requirement as the battery charges leads to decreasing efficiency in the standard converter. Further development and simulations will take place to further prove this proposed application of parallel-connected DC-DC converters.

VI. FUTURE EXAMPLE

To improve the advantages of the parallel-connected converter, a more sophisticated control algorithm must be developed. Work on a fuzzy logic controller was begun, but such a controller can become overly complicated as the number of converters increases. As previously mentioned, converter temperature must be integrated into the control scheme to help improve performance and increase robustness. A hardware implementation of the proposed parallel-connected DC-DC converter is the next step, after further simulation. In the hardware implementation, a load share manager must also be considered, along with the digital controller, to manage the even current distribution between enabled converters. One such controller is Texas Instruments' UCC39002 [12]. For the digital controller, Microchip's dsPIC33F "GS" series provides any of the features needed to implement this design.

V. CONCLUSION

Through the development of an efficiency-based model of parallel-connected DC-DC converters, it was shown that low-end efficiency can be improved over a conventional single converter. This model was developed to work as any converter topology, and to allow for easy testing of digital control algorithms. Additionally, the model can easily be modified to represent any specific converter design, based on the efficiency characteristics entered. The simulation results showed that even with a simple control algorithm, close to peak efficiency can be maintained down to 4% of full load.

An application for parallel-connected DC-DC converters was suggested. This application is in the field of electric vehicle high-power battery chargers. Further work will be done to simulate and build such a system, and tests will be carried out to compare this system with a conventional single converter.

REFERENCES

[1] H. H. C. Iu and C. K. Tse, "Study of Low-Frequency Bifurcation Phenomena of a Parallel-Connected Boost Converter System Via Simple Averaged Models," IEEE Transactions on Circuits and Systems, vol. 50, no. 5, pp. 679-686, May 2003.

[2] K. Rinne, A. Kelly, and E. O'Malley, "A Novel Digital Single-Wire Quasi-Democratic Stress Share Scheme For Paralleled Switching Converters," Powervation Ltd., Limerick, Ireland, 2010.

[3] L. Tang and S. Gui-Jia, "A Low-Cost, Digitally-Controlled Charger for Plug-In Hybrid Electric Vehicles," Energy Conversion Congress and Exposition, 2009. ECCE 2009. IEEE, pp. 3923-3929, Sept. 2009.

[4] S. M. Wang, M. W. Cheng, Y. S. Lee, R. H. Chen, and W. T. Sie, "Intelligent Charged System for Lithium-Ion Battery Strings," in Telecommunications Energy Conference, 2009. INTELECT 2009. 31st International, Incheon, 2009, pp. 1-6.

[5] N. P.R. Iyer and V. Ramaswamy, "Modeling and Simulation of a Switched Mode Power Supply Using Simulink," in Australasian Universities Power Engineering Conference, Tasmania, 2005.

[6] B. Tomescu and H. F. VanLandingham, "Imporved Large-Signal Performance of Paralleled DC-DC Converters Current Sharing Using Fuzzy Logic Control," IEEE Transactions on Power Electronics, vol. 14, no. 3, pp. 573-577, May 1999.

[7] A.D. E. Elsis and M. T. Aydemir, "Hot-Swap Parallel Operation of Boost Converters Designed for the Output of Fuel Cells," in Electrical Machines and Power Electronics, 2007. ACEMP '07. International Aegean Conference on, Bodrum, 2007, pp. 676-683.

[8] H.H.C. Iu and C. K. Tse, "Bifurcation Behavior in Parallel-Connected Buck Converters," IEEE Transactions on Circuits and Systems-I: Fundamental

Theory and Applications, vol. 48, no. 2, pp. 233-240, Feb. 2001.

[9] Texas Instruments. (2010, Mar.) Stand-Alone Synchronous Switch-Mode Lithium Phosphate Battery Charger with Low Iq. [Online]. http://focus.ti.com/lit/ds/symlink/bq24620.pdf

[10] V. Pop, H. J. Bergveld, D. Danilov, P. P.L. Regtien, and P. H.L. Notten, Battery Management Systems, F. Toolenaar, Ed. Eindhoven, The Netherlands: Springer, 2008, vol. 9.

[11] M. Broussely and G. Pistoia, Eds., Industriual Applications of Batteries: From Cars to Aerospace and Energy Storage. CPI Antony Rowe, Eastbourne: Elsevier Science, 2007.

[12] Texas Instruments. (2007, Aug.) Advanced 8-Pin Load-Share Controller. [Online].