

# Comparison of control methods for bidirectional dc/dc converters

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**Abstract** – This paper considers the use of ripple and compensator based control circuits in bidirectional dc/dc converters. Typical review of ripple based controllers includes their application in unidirectional controllers. Their advantages in terms of better transient response, simple realization and in some cases better efficacy at lighter loads are widely considered. Such a comparison must be made in the specific case when the application requires bidirectional and more importantly multiphase operation. This paper investigates by comparing three cases of a control system-standard compensator based, a constant frequency valley ripple based controller and an enhanced version including better regulation. These are compared for different voltage sources at their outputs in term of their regulation and dynamics.

**Keywords** – bidirectional dc/dc converters, control methods, Current mode control and ripple based control

## I. INTRODUCTION

Control methods for DC/DC converters can broadly be classified based on into two groups - PWM based and Ripple based. [1]

The first category includes the two common control methods for stabilization – voltage mode and current mode control [2]. A compensator circuit is needed and generally the more state variables are taken into the control algorithm the control system has, the better is the obtained dynamics. This is the reason why current mode control (involving two state variables) gives better performance generally than voltage mode control.

The second category includes converters where even faster system dynamics can be obtained by removing the compensator network entirely if possible and adding a comparator circuit. There are three general types of ripple based control – Constant on/off time, Hysteresis control and  $V^2$  control [1].

Classic comparison of these converters are made in their application in a single unidirectional converter. Using step load and other standard test various control algorithms can easily be compared.

This is not always the case however. A typical application of such converters is as a part of electric vehicle power train [3]. In this case the converter is bidirectional and the similar comparison for the dynamics offered by different control algorithms must be made. Even more, what if the bidirectional converter is modular and consists of more than one power circuit working in some form of parallel operation?

This paper tries to answer these questions by considering a multiphase bidirectional dc/dc converter and compares ripple based and standard PWM based control algorithms as a main algorithm for the design of the control system. The chosen algorithms are based on their applicability for control the multiphase converter and possible digital realization in a DSP or FPGA.

The paper is structured as follows: In the next section the models for the bidirectional dc/dc converter and two energy sources are presented. The main requirements for the control algorithm are also discussed in order to achieve optimal operation. The chosen control methods for the converter are presented and discussed in section III. Results from simulations for different load cases are presented in Section IV. Direct comparison of the used control algorithms is made in the Discussion (Section V). Finally, Section VI concludes the paper.

## II. BIDIRECTIONAL CONVERTER

A typical bidirectional converter used in energy storage systems is shown in figure 1.

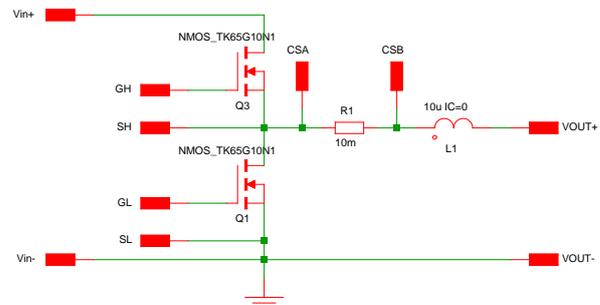


Figure 1. Bidirectional DC/DC converter

This converter can be used as a standalone power conversion stage or used as part of a multiphase system.

In bidirectional converters for operation in vehicle powertrain one of the ports of the is usually connected to some kind of energy storage (a battery or ultracapacitor) and the other port to some kind of electric motor through another bidirectional converter. The model for the two ports used in this case is presented in figure 2

The model consist of a voltage source and its series resistance (this can model a battery or ultracapacitor). The current sink can be a motor load. This generalized load model accounts for most cases of loads.

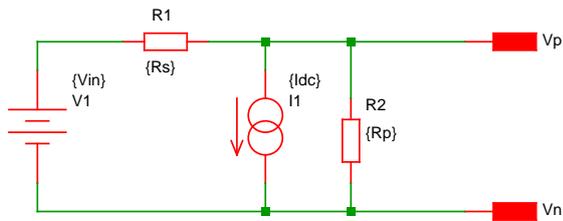


Figure 2. Bidirectional energy port

The control algorithm for this converter must be able to provide the following main functionality:

- A control loop that sets the current at a reference value. This can act also as peak current protection
- A direction pin, that controls the energy flow
- A soft start pin to gradually increase the current at start
- Over/under voltage and temperature protection
- A DCM mode conduction operation at light load to improve efficiency.
- Optimal control of more than one phase and possibly phase shedding for improved efficiency at light load

### III. CONTROL SYSTEM

Two control systems are constructed and applied to the above mentioned application – a typical current mode control and a ripple based controller with constant frequency operation with valley switching.

#### A. Compensator based control circuit

The current mode controller is shown in figure 3. It is chosen compared to the voltage mode controller as in a bidirectional converter, where both the input and output voltages are more or less independent variables in the switching interval only the inductor current is independent variable that can be controlled by algorithm and must be measured in all cases. One of the two voltages controls the charging process and possibly gives a signal for over/under voltage protection.

The circuit shown in figure 3 is a basic building block of a multiphase circuit based on compensator control.

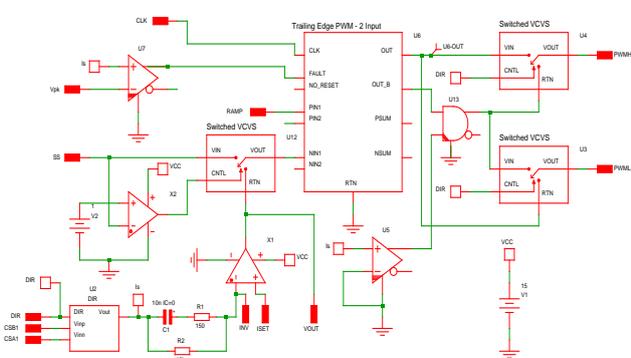


Figure 3. Single Phase Bidirectional Control Circuit with Compensator based control circuit

The main loop is composed of the positive measured current that goes to a compensator (X1 – Type 3 with external elements). This error amplifier (EA) signal goes to the negative PWM input. A standard soft start (SS) functionality is implemented by charging an external capacitor to a predetermined voltage (1V with X2 comparator) and giving the lower value from the SS capacitor or the EA output to the PWM input. Additionally a peak current protection is implemented by comparing the current to an external Vpk signal that sets the maximum current that can be obtained. If this current is exceeded RS trigger U9 ends the duty cycle early. The RAMP signal used for PWM generation is external for this block in order to have multiphase operation.

Additionally the U5 comparator forces the circuit in DCM by turning off the free-wheeling transistor when the inductor current goes to zero in order to improve efficiency.

When used as part of a multiphase more than one of the block in figure 3 are interconnected as shown in figure 4 for a two phase system. The voltage control oscillators are phase delayed to each other in this case with 180 degrees. They provide phase shifted clock impulses to the PWM blocks

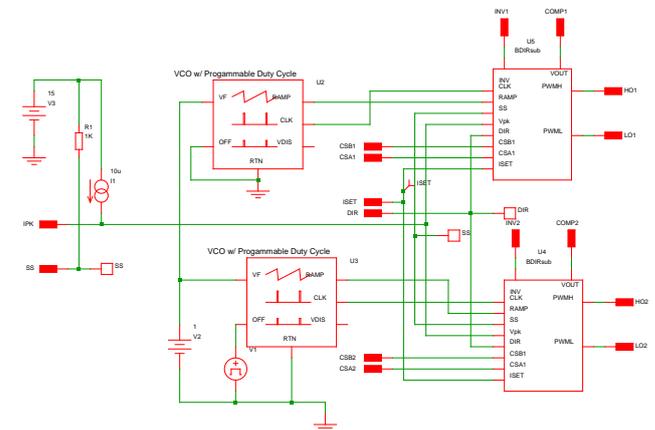


Figure 4. Multi-Phase Bidirectional Control Circuit

#### B. Ripple based control circuit

Of the three possible approaches for the realization of a ripple based controller presented in [1], [4] only the valley/peak constant switching controller is directly applicable to multiphase operation. This is done through phase shifting the clock signal.

The realized ripple based controller is shown in figure 5.

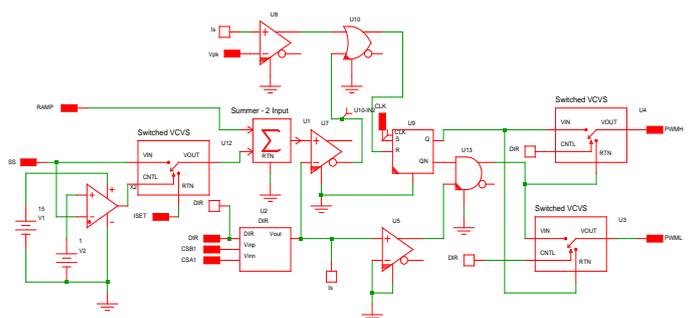


Figure 5. Control Circuit with Ripple based control circuit – Constant Frequency valley switching

The valley voltage principle of ripple based controllers operation is implemented. The start of the pulse is synchronous clock signal (phase-shifted for multiphase operation) and the reset is when the summed ramp signal and the smaller one from soft start capacitor or reference voltage becomes less than the feedback signal. The peak current protection is implemented by OR-ing the valley controller with the output of the current comparator in order to reset the pulse. The main difference between it and the one shown in Figure 3 is the removed compensator. Also here the ramp signal is used for stability concerns mainly and not directly part of the PWM process. The multiphase configuration is obtained similar to the one in figure 4. The main disadvantage with this pure ripple controller is the poor regulation as will be seen in the next section. This is the reason for adding an external compensator [4]. Adding such a compensator results in the circuit shown in figure 6.

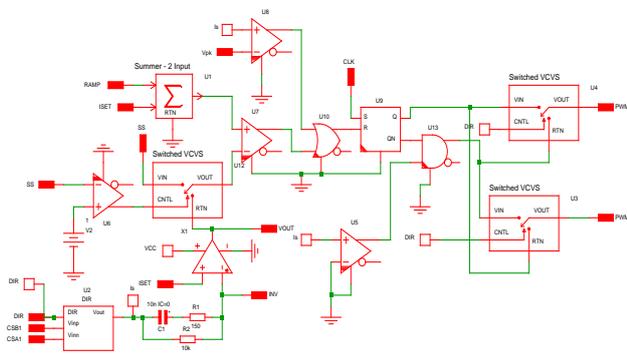


Figure 6. Control Circuit with Ripple based control circuit with improved regulation

These three circuits will be compared in the next section.

### III. SYSTEM SIMULATION

The simulated system is composed of the control system (either ripple, enhanced ripple or compensator based) and two bidirectional converters connected between common energy sources. The control system presented as a control block (for example figure 4 shows two compensator based) is controlling the circuit as shown in 7.

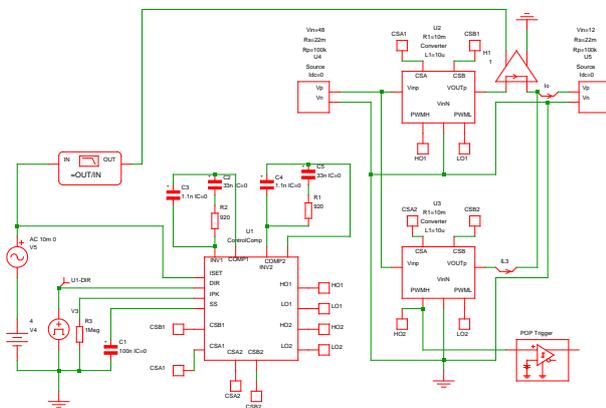


Figure 7. Single Phase Bidirectional Control Circuit with Compensator based control circuit

The circuit parameters used in the simulation are given in Table 1,2,

Two cases are considered:

- Comparison between a compensator and enhanced ripple regulator for two different output voltages
- Comparison between normal and enhanced ripple regulator for two different output voltages

The different voltages on the secondary side are set to a lower value (2V simulating for example during the charging of a supercapacitor) and a higher value (12V) to compare their operation in different bias points.

Both compensators for the enhanced ripple based and normal control are kept the same for direct comparison. A type 3 compensator has been implemented with maximum phase margin. The obtained Bode plot for the output current in terms of the set point is given in figure 8

TABLE 1. CONVERTER PARAMETERS

Inductance	10uH
Sense resistor	10mOhm
Switching Frequency	100kHz

TABLE 2. VOLTAGE SOURCE PARAMETERS

Voltage	48V	12V and 2V
Equivalent Series resistance	22 mOhm	10 mOhm
Equivalent shunt resistance	100kOhm	100kOhm
Current Sink	0	0

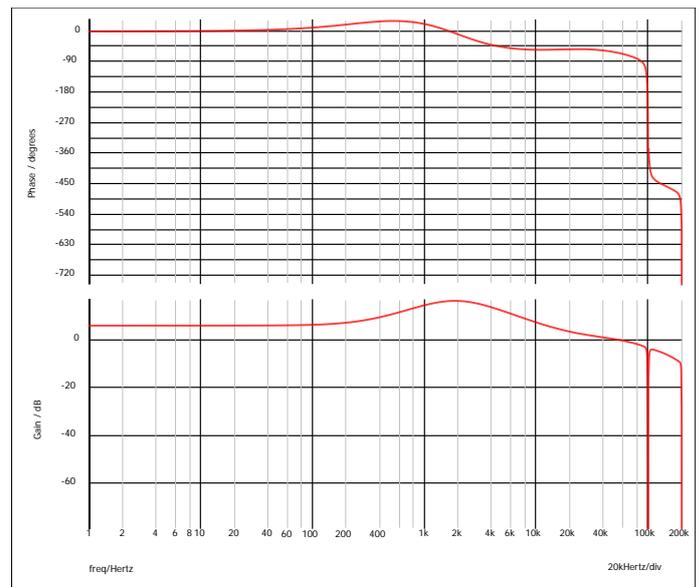


Figure 8. Closed loop Bode plot of the compensator circuit

The simulation results of the system with two ripple controllers for a rapid change in the set current direction are given in figure 9 for a 2V secondary voltage and in Figure 10 for 12V voltage

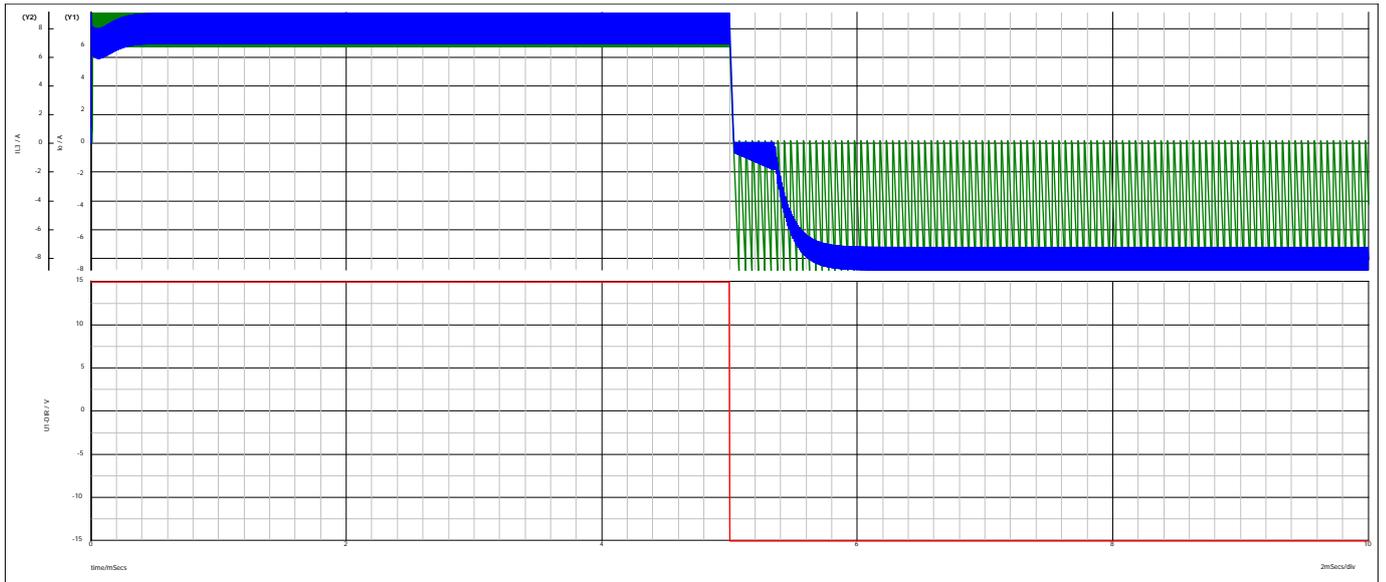


Figure 9. Comparison between Ripple based (green) and enhanced ripple controller(blue) for 2V on port 2

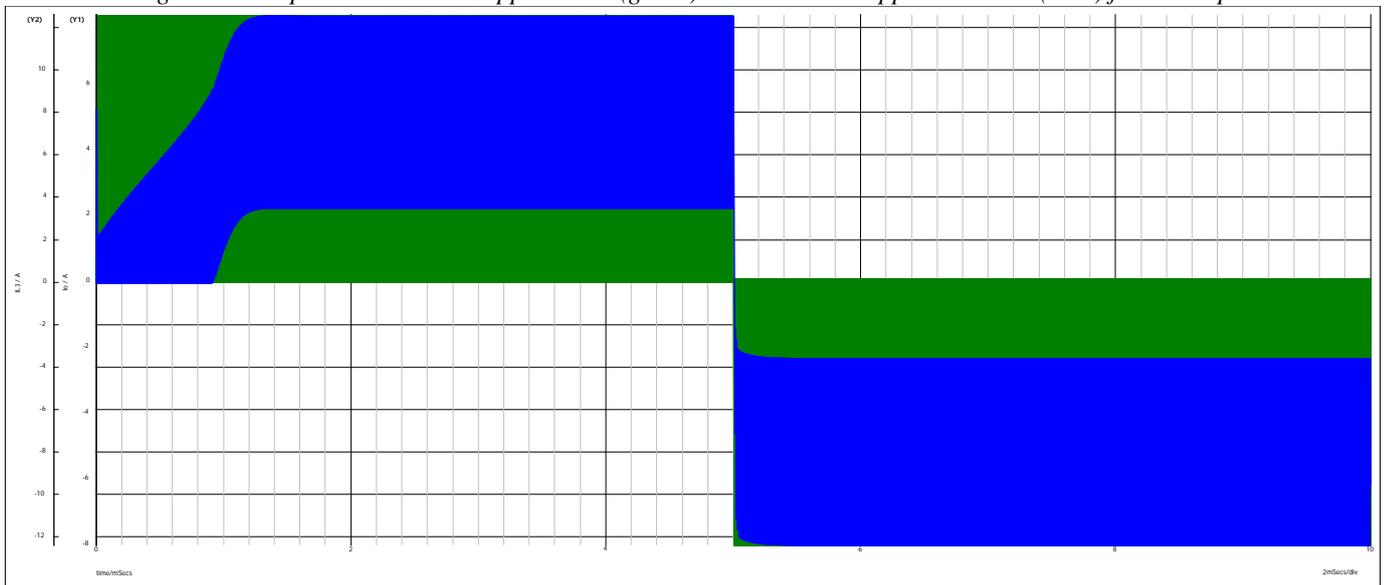


Figure 10. Comparison between Ripple based (green) and enhanced ripple controller(blue) for 12 V voltage on port 2

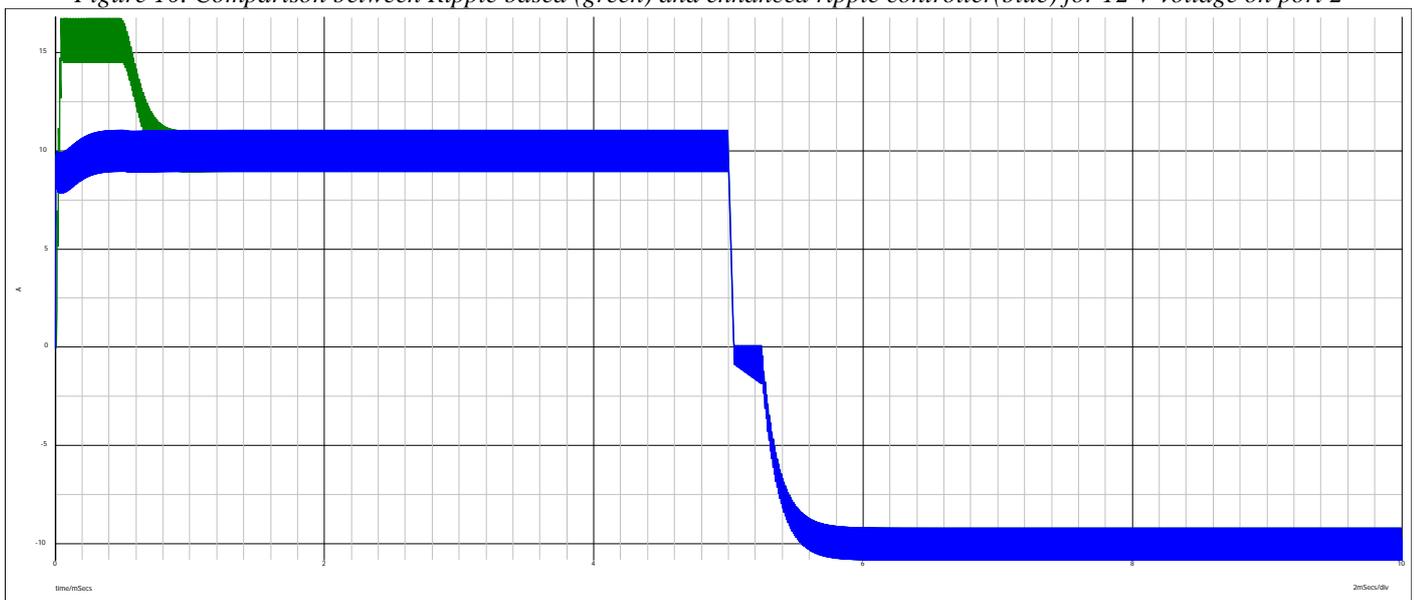


Figure 11. Comparison between Compensator based (green) and enhanced ripple controller(blue) for 2 V voltage on port 2

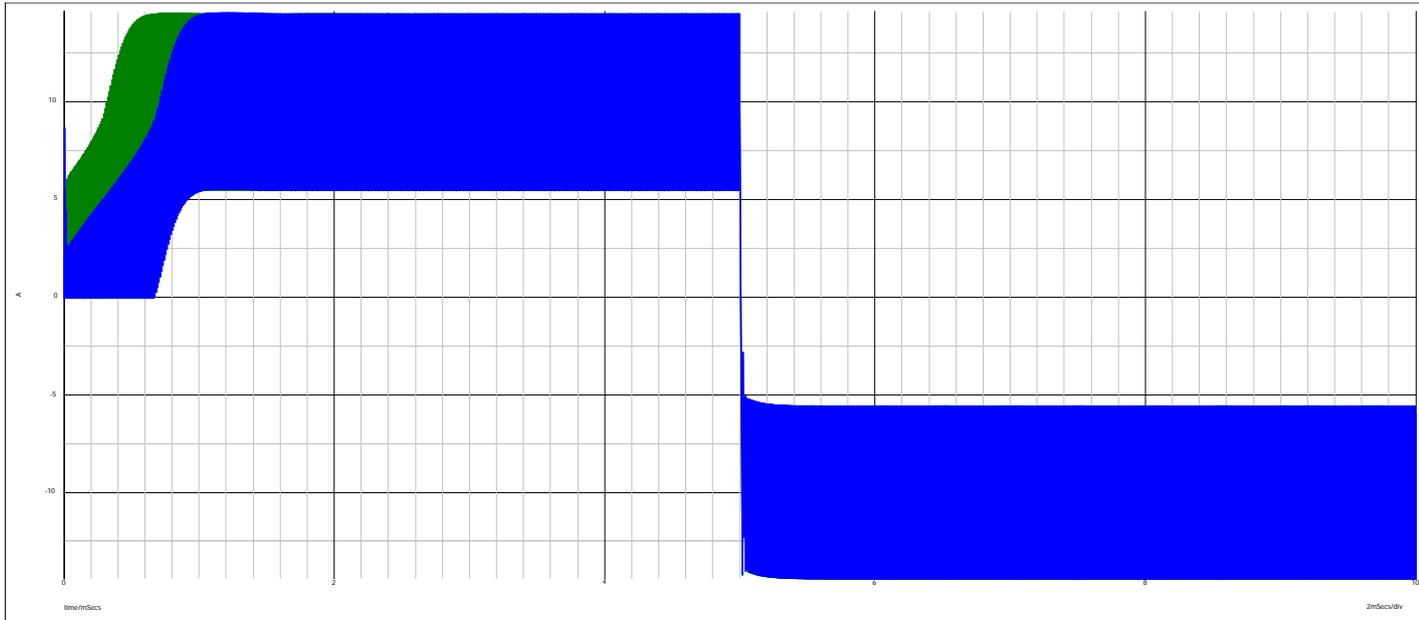


Figure 12. Comparison between Compensator based (green) and enhanced ripple controller(blue) for 12 V voltage on port 2

Figure 11 (12V) and Figure 12 (2V) gives comparison between the normal ripple based controller and the enhanced ripple based controller for two different output voltages.

#### IV. DISCUSSION

As can be seen from figure 9 and 10 the ripple based controller without compensator gives better dynamics (goes to its set point faster, especially at higher voltages) and switches faster when changing direction at low voltages, however its regulation is very poor.

From figure 11 and 12 can be seen that the enhanced ripple based has a slightly slower start up compared to the compensator approach. However, its operation is much better at low voltages as it does not go into current protection. Otherwise, their waveforms are the same during steady-state operation.

#### V. CONCLUSION

The paper compared two ripple based and a standard compensator based controllers in an application requiring a multiphase bidirectional converter. The used control methods were compared in terms of their regulation, and transient behavior when connected between two generalized energy sources.

The specific requirements of the application in terms of synchronization between control circuits for multiphase operation naturally leads to clock based system design, as these can easily be phase shifted with respect to each other, thus achieving multiphase operation.

However, the inclusion of such signals in ripple based controllers lowers their faster transient operation as evident from the performed simulation. So, methods for phase-shifted operation of hysteresis or constant on/off controllers must be sought out in the future.

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#### REFERENCES

- [1] R. Redl and J. Sun, "Ripple-Based Control of Switching Regulators—An Overview," *IEEE Trans. Power Electron.*, vol. 24, no. 12, pp. 2669–2680, 2009.
- [2] M. Truntič and M. Milanović, "Voltage and Current-Mode Control for a Buck-Converter based on Measured Integral Values of Voltage and Current Implemented in FPGA," *IEEE Trans. Power Electron.*, vol. 29, no. 12, pp. 6686–6699, 2014.
- [3] S. Dusmez, A. Hasanzadeh, and A. Khaligh, "Comparative Analysis of Bidirectional Three-Level DC–DC Converter for Automotive Applications," *IEEE Trans. Ind. Electron.*, vol. 62, no. 5, pp. 3305–3315, 2015.
- [4] G. Zhou, J. Xu, and J. Wang, "Constant-Frequency Peak-Ripple-Based Control of Buck Converter in CCM: Review, Unification, and Duality," *IEEE Trans. Ind. Electron.*, vol. 61, no. 3, pp. 1280–1291, 2014.