Performance Fuzzy Logic Control to Minimize Output Voltage Ripple and Balanced Current Distribution of DC-DC Converters in Parallel Non-Identical

Bambang Suprianto[1], Mochamad Ashari[2], and Mauridhi Hery Purnomo[3]

***Abstract*—Analysis of DC-DC converters are arranged in parallel with the inductor parameters which are different from what discussed in this paper. Buck DC-DC converter using non-identical model, that is different in the value of inductance which is $L_1 \neq L_2 \neq L_3$. Research techniques are taken from the difference of current flows of each converter i.e. I_1-I_2 and I_1- I_3 and the reference current is I_1. This current difference results are used as input controller. PID and Fuzzy Inference System with 5 gbell membership function are used as a controller. The results of this study indicate a significant system performance. Output voltage ripple is 10 mV with the total output current is 63.7 Ampere. Each DC-DC converter provides a current of contribution to the load 21.28 Ampere. The difference of the current distribution of each converter module range is 1mA - 4mA RMS (Root Mean Square) using PID control, while using Fuzzy Logic Control for differences in the distribution of current is 0.1 mA RMS and the output voltage is 48 volt. Fuzzy Logic Control performance has shown an improvement of control systems to reduce the output voltage ripple and the ability to share load current equally into each DC-DC converter.**

Keywords—**DC-DC Converter in parallel, Current-sharing loop, Fuzzy Logic Control (FLC)**

I. INTRODUCTION

Article control DC-DC converters in parallel is to equalize the current in each converter and ensures the stability of the output voltage at the load. Parallel system of power converter is to add complexity and require several treatments and the cost. Control techniques are needed to ensure a balanced distribution of the current and effectiveness of controls, especially for a large load [1]. This paper presents a digital control on the step-down converter using a fuzzy state space controller. Draft state controller is designed to eliminate start-up overshoot and reduce dynamic errors, but the state controller is less able to eliminate the steady-state error so that improvement of weakness over the two algorithm developed. The first state controller with constant reinforcement in combination with decomposed fuzzy PID controller and the fuzzy state space controller. Both control systems are treated in continuous current mode operation. The results of experiments are conducted using 16-bit DSP units, and the second matching algorithm is implemented with FPGA [2].

Bogdan Tomescu, On the Use of Fuzzy Logic to Control Paralleled DC-DC Converters, introduces fuzzy logic control applications, the development of mathematics and proves the concept and benefits through a comparison of existing simulation, the classical and methods.

A stable fuzzy logic control in a master-slave current sharing loop DC-DC converters in parallel is presented in this paper by considering the performance improvement of large signal, small signal compensators, and control systems. Because of the complexity of the system, design of small signal can not provide good response time of the large load changes and at the transient. Fuzzy logic control with nonlinear control system provides a superior type for this application. Design using a PID controller with fuzzy rules of inference, the simulation shows a good transient response and wide load changes from 25% to with a nominal 75% load. Current sharing control is formulated as a tracking problem and ensures stability in the trajectory adaptation Lyapunov control. Above the control, techniques provide an advantage in overcoming the problems in the model complex systems, a practical tool, and are suitable for both analog and digital implementations. [3] This paper presents the use of Fuzzy Logic Control as a controller, where the current distribution of each DC-DC converter is used as an input. Parallel DC-DC converter non-identical features inductance values are not equal, where L_1 is 100 mH, L_2 is 105 mH and L_3 is 110 mH. They use the DC-DC converter Buck model. The data are processed from output current of each DC-DC converter which is arranged in parallel. They are I_1-I_2 and I_1 - I_3 and the reference current is I_1. The output voltage is Vo and the method of Current Mode Control (CMC) is used as input FLC. For futher detail see in Fig. 1.

$God_1(s) = God_2(s) = God_3(s)$ = module DC-DC converters,
G(s) = transfer function compensation circuit,
Q(s) = output impedance transfer function,
$k_1 = k_2 = k_3$ = Amplifier PWM DC-DC converter.

Fig. 1 can clarify the relationship between each DC-DC converter module. In this study, each DC-DC converter module non isolation is independent. The difference is used as an input process control and compensation amplifier is used for switching of power component. The Matlab Simulink is used as a tool to analyze parallel DC-DC converters system. Parallel DC-DC converters non-identical is the development of existing models, therefore this research discusses the concept, simulation and analysis of the parallel DC-DC converter non-identical.

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II. DC-DC CONVERTER PARALLEL

Parallel DC-DC converter has been widely used in power systems. One basic objective of parallel DC-DC converter is to share the load among the constituent converters.

To do this, some forms of control have 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 [4]. In general, methods for the paralleling DC-DC converter are described in the connections model, control configuration and feedback functions although some forms of classification and comparisons have been given for paralleling schemes [4], [5].

Kirchhoff's second law approach is a method that allows to discuss the parallel connection. Considering DC-DC converter as either voltage sources or current sources, the development of models can be used in the analysis. Furthermore, control method will be systematically introduce to complete the output regulation and current sharing functions. Two basic laws must be followed when connecting the voltage source together. First, Kirchhoff's Voltage Law (KVL) states that none of the two independent voltage sources is allowed to connect in parallel.

Theoretically, even if the voltage source with the same magnitude, they are still not allowed as a form of lawlessness KVL and make the current values undefined [5, 6, 9]. Similarly, Kirchhoff's Current Law (KCL) connects two independent current sources in series. From the previous discussion, it is clear that any scheme involving parallel voltage and current sources must comply with two basic structures that have been described previously. It is also discussed that the voltage sources are not perfect so there are three basic configurations for parallel sources not perfect. DC-DC converter is treated as a source of voltage or current source is not perfect, the three basic configurations for DC-DC converter can be developed in parallel. For more details, the type of configuration will be discussed further. For the parallel connection of voltage obtained by the following formula:

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

Meanwhile, a parallel connection of current sources obtained based on the formula:

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

III. 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. 2 (a). Each branch represents a converter, which is basically a Th´evevin 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 Th´evenin 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. 2(b). In this configuration, each converter is a dependant voltage source, in which the output voltage is controlled directly. The currents sensed from different converters are 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 (a), one converter serves as the voltage (Th´evenin) source and others are current (Norton) sources. The control structure without current-sharing loop is shown in Fig. 3 (b). There is a main voltage feedback loop, which acts on the voltage (Th´evenin) source to regulate the output voltage. Other branches are under current-mode control (peak-current-mode control is applied in the paper), that the objective is to make all individual output currents share the same portion of the load current. For Type II configuration with current-sharing loop, the control structure is shown in Fig. 3 (c). 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 masterslave 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. 4 (a), 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. 4 (b). 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 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. 4 (c).

IV. BUCK DC-DC CONVERTER

Topology DC-DC converter Buck model is used in this study. Current Mode Control Method is an appropriate concept for the parallel system, because this study developed three DC-DC converters in parallel non-identical parameters of the inductor. DC-DC converter Buck model, operated in a continuous state if the current flowing in the inductor L_1, will never reach commutation zero during the cycle occurs. This phenomenon can be described as follows: the first time on the condition ON MOSFET, $V_L = V_i - V_o$ and the inductor current I_L rises linearly while the diode in reverse biased so no current flows in the D1. Both at the time of MOSFET in the OFF state diode becomes forward biased so that $V_L = - V_o$, this condition causes the inductor current decreases gradually.

The role of inductor L_1 is to transfer energy from the input to output with a large stored energy during ON and released at OFF condition, the magnitude is:

$$E = \frac{1}{2} L \times I_L^2 \tag{3}$$

and

$$V_L = L \frac{dI_L}{dt} \tag{4}$$

I_L was a change occurs in two conditions namely, ON condition when the amount is:

$$\Delta I_{L_{on}} = \int_0^{t_{on}} \frac{V_L}{L} dt = \frac{(V_i - V_o).t_{on}}{L} \tag{5}$$

OFF condition when the amount is:

$$\Delta I_{L_{off}} = \int_0^{t_{off}} \frac{V_L}{L} dt = -\frac{V_o.t_{off}}{L} \tag{6}$$

it can be assumed that the stored energy component of L in one period T resulting from the two conditions above the current changes are:

$$\Delta I_{L_{on}} + \Delta I_{L_{off}} = 0 \tag{7}$$

So, the equation is as:

$$\frac{(V_i - V_o).t_{on}}{L} - \frac{(V_i - V_o).t_{on}}{L} = 0 \tag{8}$$

In the Fig. 5 can be seen that t_{on} = D. T, while the t_{off} = T - T. D, where D is a scalar quantity called the Duty Cycle.

The value of D is between 0 and 1, so the decrease in D formula is:

$$(V_i - V_o).D.T - V_o.(T - D.T) = 0 \tag{9}$$

The equation can be written as the following,

$$V_o = D.V_i \quad or \quad D = \frac{V_o}{V_i} \tag{10}$$

V. GBELL MEMBERSHIP FUNCTION

Membership function is a curve that shows the mapping of data input points to the value of membership or so-called degree of membership, with the interval is between 0 and 1. In general the parameters a and c is the membership function as the following equation:

$$f(x;a,b,c) = \frac{1}{1 + \left|\frac{x - c}{a}\right|^{2b}} \tag{11}$$

b parameters in general is positive, c parameter is located in the middle of the curve while a parameter is the inflection point that determines the width of the narrow curve shape. [8.9] Membership Function used in this research is 5 gbellmf. For input *Ve (Verror)* , *ΔVe (delta Error)* and Output membership function can be seen in Fig. 6. The range of output membership function determines the ability to control action on both the input variables *Ve* and *ΔVe.* So the range of output membership function is very influential on the output quality of a system designed.

VI. RESULTS AND DISCUSSION

Table 1 is a parallel DC-DC converter Parameters. Parallel DC-DC converter non-identical is composed of general components and Current Mode Control is subtracting of current method from each converter. Analysis and simulation use Simulink of Matlab.

These results provide a positive contribution to the stability of output voltage, current distribution of each DC-DC converter and output voltage ripple which is smaller than the output voltage ripple when the parallel system does not use control. Output voltage response to load about is 30 Ampere and output voltage still stable ± 48 volts although the initial response to the voltage rises to 53 volts. This condition takes only 0.05 seconds. Fig. 7 is a response to the output voltage Vo and I_1, I_2, and I_3, with a change in $R_L = 1.5\ \Omega$ to 0.75Ω using Gbell Membership Function. While the transient responses, the output voltage decreases to 30 volts, caused by a change in the load from 30 Ampere up to about 63 Ampere.

This phenomenon also takes approximately 0.1 seconds to reach a stable output voltage again. Distribution of current to the load on the DC-DC converter based on the initial FLC has a quite big difference between each module about tens of mA. After a change of the load occurs, however, the difference of current distribution of each converter module becomes dozens mA. The difference between the first and second converters is only 0.0001182 mA, and the difference between the first and third converter becomes 0.0001095mA.

Fig. 8 is the result of DC-DC converters in parallel by using PID controller but the response has a little change compared to the control system by using FLC. Rise-time is really fast, the voltage give a little increase in the beginning. At steady-state, the distribution difference of 10A load is tens mA.

When the load is increased to 21 Ampere of each module DC-DC converter, the differences of current distribution for each DC-DC converter change into 0.1 mA up to 1 mA.

TABLE 1.
DC-DC CONVERTER PARAMETER

Component	1st Converter	2nd Converter	3rd Converter
Mosfet	Same type	Same type	Same type
Inductor	100 mH	105mH	110 mH
Capasitor	2200 uF	2200 uF	2200 uF
Diode	Same type	Same type	Same type
R_L(Load)		1.5 Ω - 0.75 Ω	
Fs		5000 Hz	

The output voltage ripple is less than 10 mV, while the systems are not using controller, the ripple is in range 100 mV. See Fig. 9 for comparing the results of paper [2]. The output voltage ripple is 39 mV by using PID and Fuzzy state control. The output voltage ripple is 11 mV. In this study, the systems to minimize the ripples have been achieved. From the study results, the difference of current distribution of each DC-DC converter module give a good performance and the difference of current distribution is range from 4 mA up to 8 mA. Fig. 10 is an enlarged figure of current distribution on the full load and PID Control as a controller in this system. Fig. 11 shows the difference in the distribution of current response to the full load using FLC.

The difference between the first DC-DC converter module and the second DC-DC converter module is 0.0001182 Ampere (0.1 mA), while the difference of current distribution between the first converter module and the third DC-DC converter module is 0.0001095 Ampere (0.1 mA) .

The results of the response Fig. 12 is the MOSFET gate trigger pulse to the module DC-DC converter first, a large voltage is 1 Volt is a system integrator to control the control on this research, in order to balance the current distribution as even greater value. This technique is done in analyzing parallel DC-DC converters non-identical parameters.

The results of the response Fig. 13 is the MOSFET gate trigger pulse for the DC-DC converter module for the second and third. The tension is about 35 volts and the integrator use to control system so that current distribution becomes equal from each DC-DC converter.

Fig. 14 is percentage response current distribution between I_1 and I_2. I_1 and I_3. The figure shows the difference in the distribution of current in the small load become 10%, but the difference of current distribution is below 5% at the large load. The design of parallel DC-DC converter using FLC had a good response at large load.

VII. CONCLUSION

This study produced DC-DC converters system in parallel with the inductance parameters $L_1 \neq L_2 \neq L_3$, using Fuzzy Logic Control and PID control systems as an analysis comparison. The improvement of output voltage ripple is about 10 mV, and the difference of current distribution to the load becomes 0.1 mA (near 0%). Those three different DC-DC converters module (The first, second, and third) resulting the same number that is 21.28 Ampere by using FLC. Meanwhile, by using of PID control made the difference of current distribution become 4 mA - 8 mA, in which the current distribution of each DC-DC converter module for the first converter is 21.13, the second converter is 21.13 Ampere and the third converter is 21.12 Ampere. In conclusion, some system repairmen had been carried out to the parallel DC-DC converter non-identical.

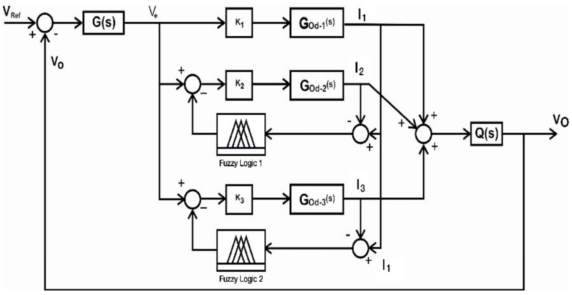

Fig 1. Block circuit DC-DC converter three non-identical parallel

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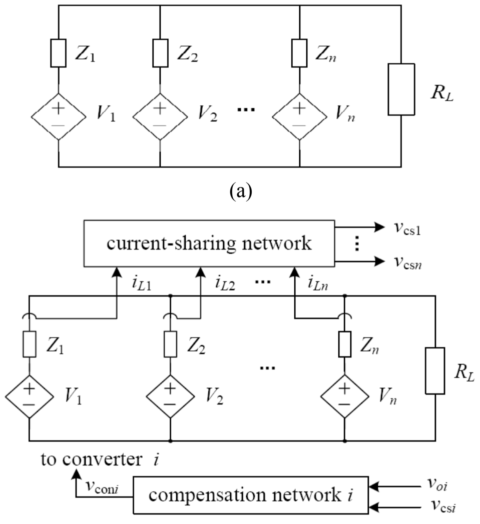
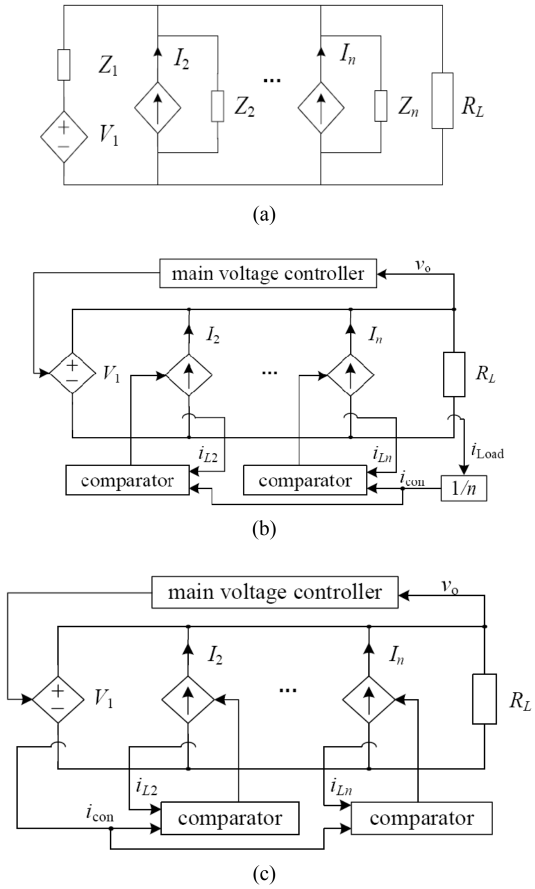


(a)

(b)

Fig. 2. (a) Configuration DC-DC converter Type I (b) The current sharing loop system

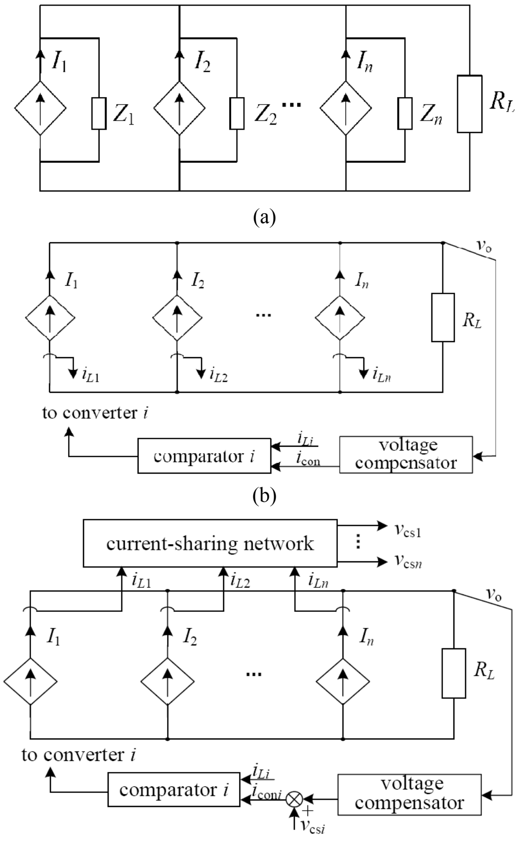


(a)

(b)

(c)

Fig. 3.(a) Configuration DC-DC converter Type II. (b) Configuration without loop current sharing (c) Configuration using the loop current sharing



(a)

(b)

(c)

Fig. 4. (a) Configuration DC-DC converter type III (b) Configuration without loop current sharing (c) Configuration using the loop current sharing

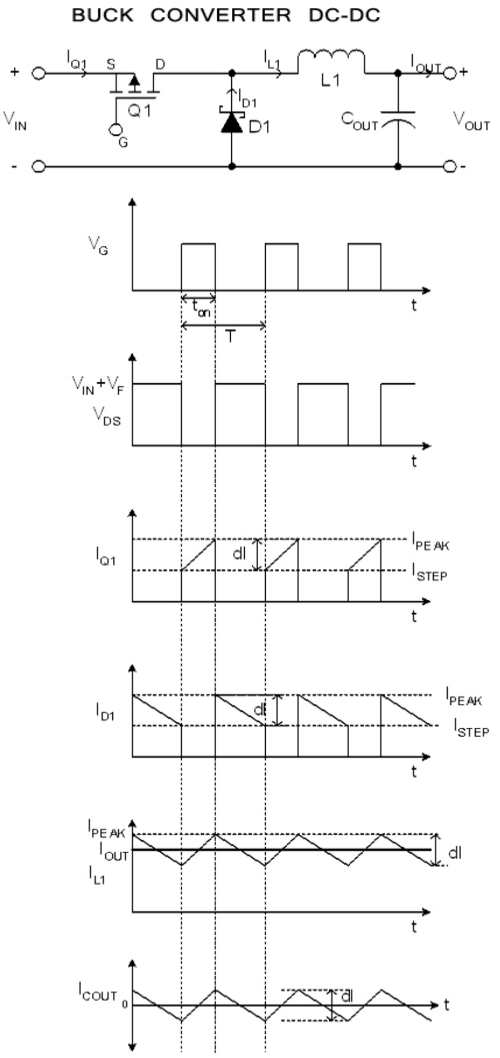


Fig. 5. DC-DC converter model of Buck

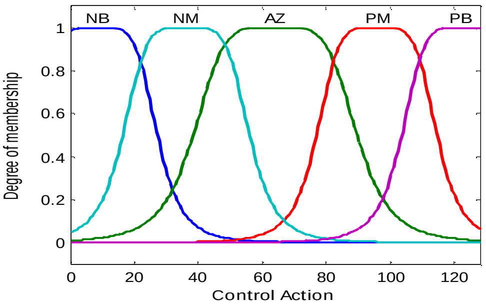


Fig. 6. Membership function output

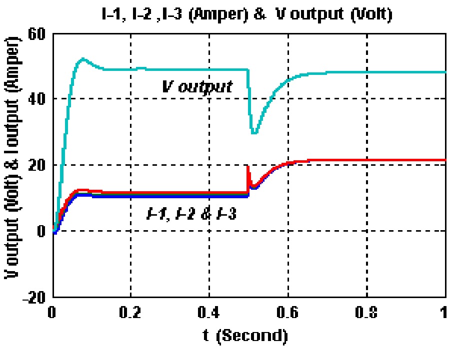


Fig. 7. Voltage and current responses Vo, I-1, I-2 & I-3 using fuzzy logic control

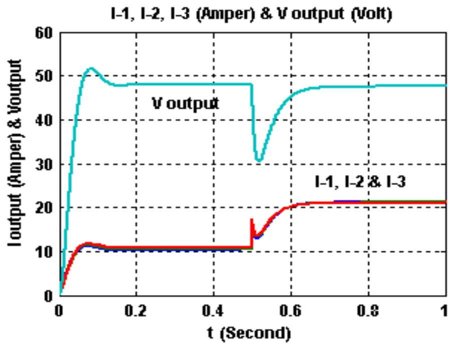


Fig. 8. Voltage and current responses Vo, I-1, I-2 & I-3 using the PID Control.

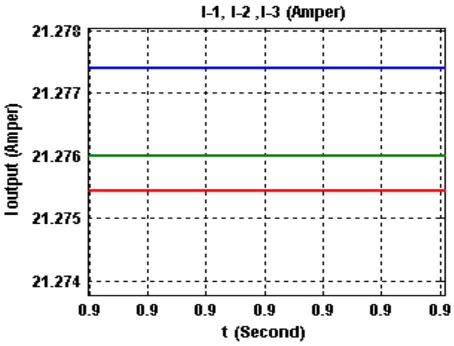


Fig. 11. Current output differences, I-1, I-2 & I-3 using fuzzy logic control

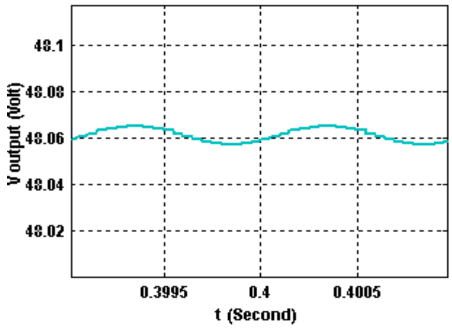


Fig. 9. The output voltage ripple at 48 Volt

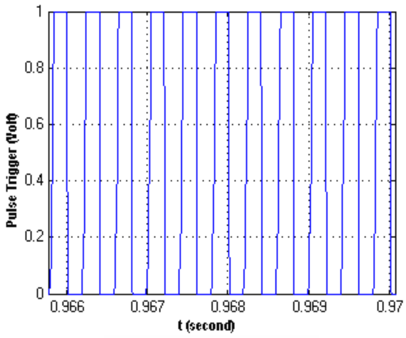


Fig. 12. Pulse trigger gate MOSFET for the first DC-DC converter module

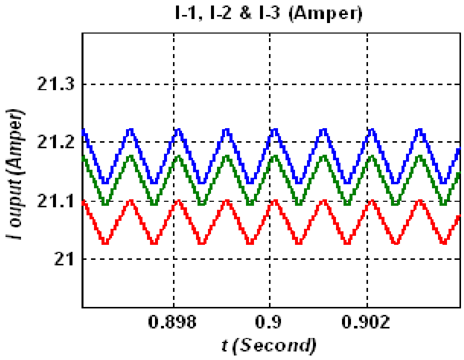


Fig. 10. Output current differences, I-1, I-2 & I-3 using PID Control.

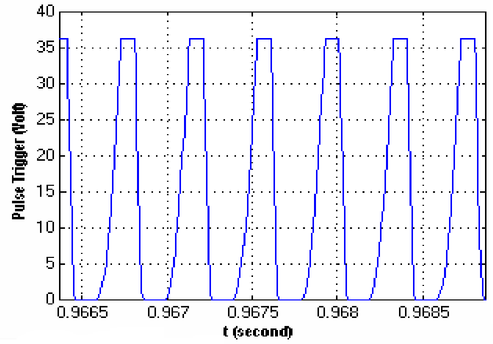


Fig. 13. Pulse trigger gate MOSFET for the second and the third DC-DC converters module

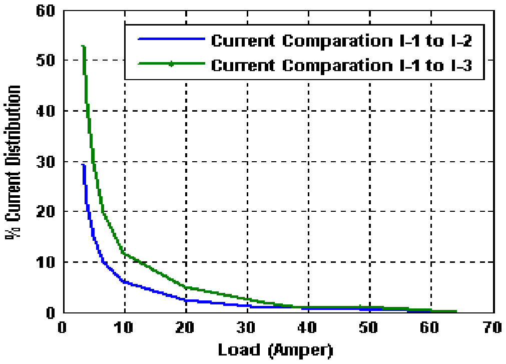


Fig.14. Comparation Percentage are between I-1 and I-2 , I-1, and I-3 at the load about 5 Ampere - 60 Ampere