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EQUAL USAGE OF EACH POWER SUPPLY IN A SCALABLE PARALLEL CONFIGURATION

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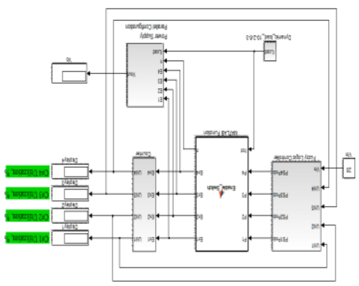
Graphical abstract



Abstract

In this paper, a fuzzy logic controller determines the turning ON or OFF of a power supply in a scalable *n*-parallel power supply configuration. Each power supply is modeled using differential equations and only differs in the values of its parasitic resistances. This is done in a MATLAB/Simulink environment. A fuzzy logic controller accepts the power supply usage and the power supply's input voltage perturbation as its inputs while the probability of the corresponding power supply turning ON is its output. The power supplies are connected in parallel configuration and tested under various conditions of static and dynamic current sharing load, voltage input perturbations and on the total number of active power supplies in a given parallel configuration. The number of power supplies *n* in the parallel configuration is changed by adding or removing a power supply. This addition or removal is termed as scalability. As a result, the fuzzy logic controller was able to guarantee that all power supplies in the scalable *n*-parallel configuration have equal usage while sharing the load current equally under a regulated output voltage.

Keywords: Equal usage, scalable parallel configuration, fuzzy logic controller

1.0 INTRODUCTION

DC-DC power supplies connected in a parallel configuration offer system reliability due to its redundancy, system flexibility due to modularity, and stability due to reduced thermal stress since each power supply handles a lower power level [1]. The design considerations for a single power supply capable of providing a high amount of power are further simplified in terms of power density; parts count density, electromagnetics, etc. through parallel power supplies.

In an *n*-parallel DC-DC power supply system, where *n* denotes the number of power supplies, each of the power supplies must equally share the load at all times. The type of current-sharing mechanism employed in a parallel setup ensures equal load sharing [2, 3, 4, 5]. This implies that all power supplies in the parallel DC-DC system are always turned ON regardless of what load is connected to the output ports. For light load, it is possible to allow the parallel system to turn OFF other power supplies as long as the remaining functional power supplies can support the required load.

Several research studies have tackled this issue. In [6], a digital controller was designed to determine the possible number of power supplies to be turned ON under load condition. The DC power supply was modeled by using lookup tables containing efficiency characteristics. In its simulation experiments, four DC power supplies were used, each capable of delivering 384W at a maximum load of 8A. As the load increases, power supplies are sequentially turning ON to equally share the load. A similar work in [7] was seen. However, instead of using efficiency tables for power supply modeling, a Simulink model, based on [8], was used to develop the buck power supplies. In [7], the elementary and simplified control simply determines the number of power supplies needed (*n*) to be turned ON based on the output current as seen by the parallel configuration. This was determined by:

$$n = N - floor\left\{\frac{NI_{ox(\max)} - I_{out}}{I_{ox(\max)}}\right\} \quad (1)$$

where:

- $I_{ox(max)}$ = output current limit of power supply x
- I_{out} = load current
- N = number of available power supplies in the parallel configuration
- n = number of power supplies to be turned ON.

Another work where the number of power supplies were also varied can be found in [9]. However, it must be pointed that the objective of adding power supplies in the parallel configuration is to regulate the output voltage and is governed by:

$$V_{out} = DV_{in} - \frac{r}{N}I \quad (2)$$

where:

- V_{out} = output voltage
- D = duty cycle (=50%)
- V_{in} = input voltage
- r = internal resistance
- N = number of DC-DC power supplies
- I = load current

This control strategy is different from the conventional method and operates in an open loop configuration. Another observation is that the internal resistance r is assumed to be constant for all power supplies in the parallel configuration. This, however, is not achievable in an actual power supply parallel configuration.

The research undertakings in [6, 7, 9] all operate sequentially. In practical implementation, the first power supply is always turned ON and would normally be the first to fail among its counterparts due to stress and component wear and tear.

In the follow-up studies in [10, 11], a fuzzy logic controller was used to improve the performance of the elementary and simplified control. This improvement addresses the sequential turning ON or OFF of the power supplies. Also, one of the non-idealities in a power supply such as the input voltage perturbation was considered. Other factors such as thermal stress, ambient temperature and fault conditions may also be incorporated but were neglected due to modeling issues and concerns.

Fuzzy logic is a non-linear intelligent control associated in the emulation of human thought processing. Its usage in the power electronics sector has increased due to the development of high-speed processors, its robustness to nonlinearities present in power supplies and its simplicity in design [12]. For most accomplished research work, fuzzy logic was used as control schemes in maintaining constant output voltages at varying load and disturbances, improve current-sharing abilities of parallel power supplies and reduce switching losses [13, 14, 15, 16, 17].

In [10, 11], the fuzzy logic controller succeeded in equalizing the usage of all power supplies in the parallel configuration while maintaining equal current sharing among remaining functional power supplies needed to supply the load even though each implemented a different modeling approach for the power supply. The model used in [10] followed the model in [7] while [11] employed the model in [18].

Also, the research work in [10] was extended in [11] by providing a point where a balanced power supply usage will occur during dynamic loading. Dynamic loading is characterized by a change in the load current over a certain time interval, in contrast with static loading which remains constant all throughout the test. Power supply usage, expressed in percentage, is defined as the ratio of the of a power supply's turn ON time over the sum time of all power supplies' turn ON time. The derived expression predicting the percentage where the power supply's usage (U_{conv}) will be equal during dynamic loading was shown to be:

$$U_{conv} = \frac{1}{N}\sum_{x=1}^{n}\frac{t_{ONx}}{t}\,ceiling\left(\frac{I_x}{Io_{\max}}\right) \text{x}100\% \quad (3)$$

where:

- N = number of power supplies in parallel
- x = i^{th} current load in the dynamic loading condition
- t_{ONx} = duration of a load current in x dynamic loading
- I_x = load current x in dynamic loading
- $Io_{\max}$ = maximum output current of a single power supply
- t = period of dynamic loading.

Equation (3) can also be used in static loading. For static loading, $t_{ONx} = t$ for x = 1, 2, 3, …, n, where n depicts how many dynamic loading conditions occurred.

From [11], the following are noteworthy observations from a given number of power supplies in the parallel configuration and maximum load current:

1. There are many and different combinations of dynamic loading that may arrive at the same power supply usage percentage. This is due to the fact that a power supply can source a range of load currents. For example, a power supply with maximum load current of 2.5A can both supply a 2A- and 1.5A load.
2. The possible values of U_{conv} are restricted and directly proportional to the number of power supplies included in the parallel configuration, as seen in Equation (3) i.e. $U_{CONV} \propto \frac{1}{N}$.

To ensure that while the fuzzy logic controller was able to equalize the power supply usage, the current sharing of the remaining active power supplies must also be checked. The expression that computes for the current sharing error (*%CS*) is given in Equation (4). I_{ox} is equal to the output current of the parallel power supplies while I_{tot} is the total current that the parallel power supplies can supply [18].

$$\%CS_{Error} = \left| \left\{ 1 - \frac{I_{ox}}{\frac{I_{tot}}{N}} \right\} \right| \times 100\% \qquad (4)$$

A simulation experiment was run to test the system during dynamic loading. In this setup, the input voltage is modelled by adding a Gaussian noise with varying variance around the desired input voltage 20V. [10, 11] have proven that active power supplies in their initial four-power supply setup were able to equally share the load while determining the point of equal power supply usage.

Finally, we summarize to the best of our knowledge, our original contributions in this research work.

1. We developed and simulated a fuzzy logic controller aimed at equalizing converter utilization under a scalable configuration. The proposed controller is designed by using only a combination of linear membership functions (triangular and trapezoidal). This design concept was taken into consideration to provide ease in hardware development.
2. It will be shown that when previous run times of used converters are considered, the fuzzy logic controller is still able to equalize all usage times of the converters while at the same time still achieving current sharing among involved power converters.
3. The relationship between the number of converters, their previous usage times, load capacities, and equalized converter utilization are mathematically derived and verified extensively using simulations under various testing conditions of static and dynamic loading.
4. Finally, we believe that this concept of equalizing converter utilization under various conditions by intelligently turning ON or OFF active converters is a first in this field. Most developed current sharing techniques rely on turning ON ALL converters at the same time [1, 2, 3], thus the results presented here are original and has no basis to be compared with. This work is related to the concept found in [19] that improves tollgate server utilization and vehicle waiting time.

2.0 METHODOLOGY

In this research, an extended application of the initiatives done in [7, 10, 11] focusing on the scalability of the proposed scheme is presented. The block diagram of the proposed intelligent system is shown in Figure 1 below.

The control strategy is extended to a scalable *n*-parallel power supply configuration where power supplies are either added or removed to increase or decrease the number of available power supplies in the *n*-parallel configuration that can support a given load.

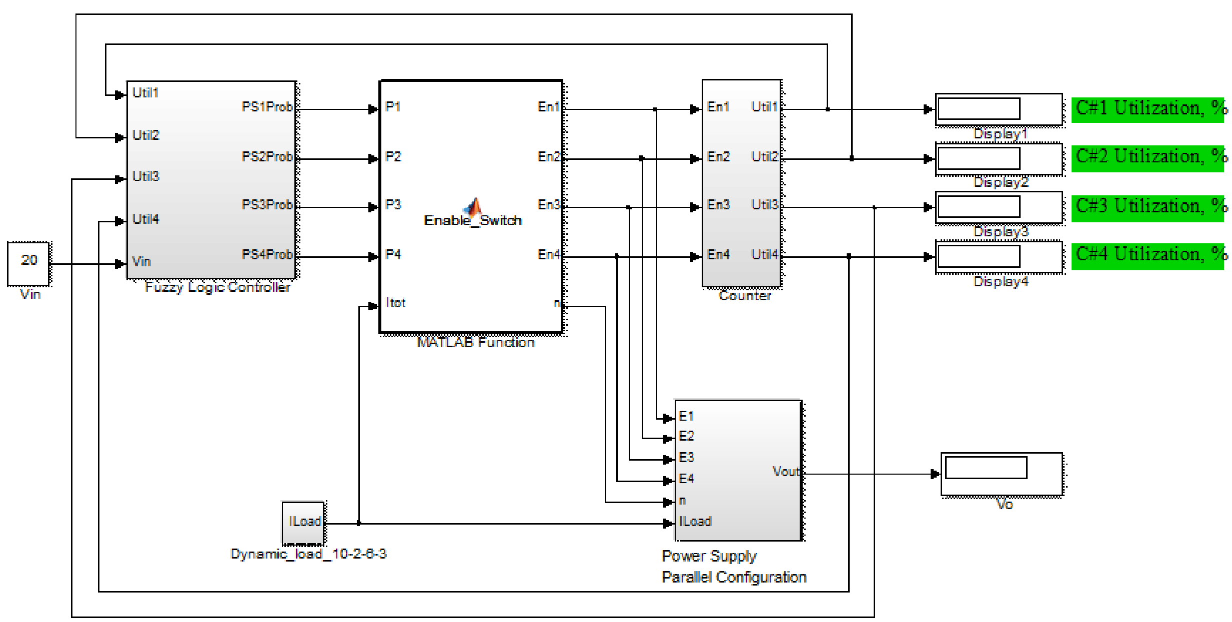


Figure 1 Simulink Model of a Parallel Power Supply Configuration with a Fuzzy Logic Controller

The "Power Supply Parallel Configuration" block houses the scalable *n*-parallel DC-DC power supplies. Initially, there are four power supplies present in the parallel configuration shown by the number of available enables, $E_{X=1,2,3,4}$.

Table 1 summarizes the power supply specifications used in each of the power supply that is to be added or removed from the *n*-parallel configuration.

The "Matlab Function" block controls the turning ON and OFF of a DC-DC power supply through Enx, where $x = 1, 2, 3, \ldots, n$, is the power supply number enable.

The "Fuzzy Logic Controller" block optimizes the usage of each power supply in the scalable *n*-parallel configuration.

Table 1 Power Supply Specifications

Specifications	**Value**
Input Voltage	20V
Output Voltage	12V
Output Regulation Band	±0.2V
Maximum Load Current	2.5 A
Minimum Load Current	0 A
Switching Frequency	100kHz
Inductance	49.08uH
Capacitance	153.4uF

The inputs of the proposed fuzzy logic controller are the converter usage and its corresponding input voltage perturbation and its output is how probable is a converter to be chosen to supply the required load. These were chosen to place more weight on how long a certain converter has been used already since our objective is to equalize all converter utilizations. The input voltage perturbation was chosen to provide another criterion on how to further improve the selection of which power supplies to turn ON. The corresponding membership functions for the inputs to the fuzzy logic controller are shown in Figure 2 and Figure 3 while the output membership function is shown in Figure 4.

The linear membership functions were chosen by considering how easy and fast it is to implement linear functions in a digital computer.

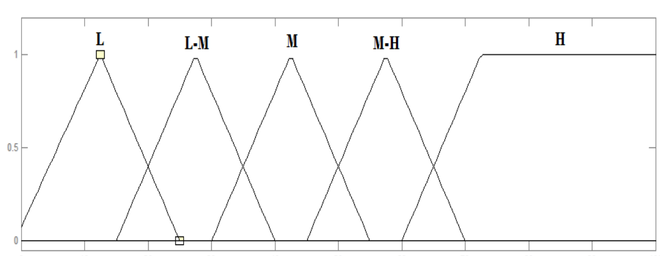


Figure 2 Membership functions for power supply usage

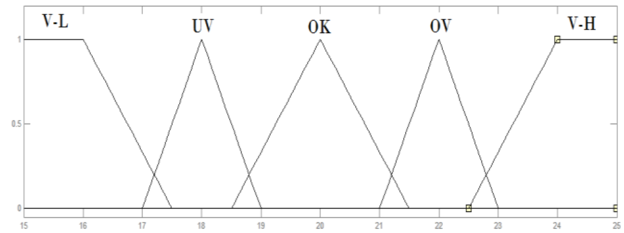


Figure 3: Membership functions for input voltage perturbation

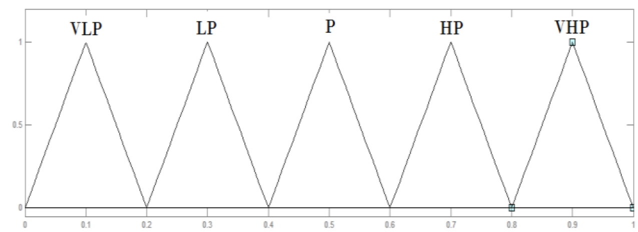


Figure 4 Membership functions for the probability of turning ON

The power supply usage input ranges from 0-100% while the input voltage perturbation is set to vary from 15-25 volts. Since the output is a probability, the range is simply from 0 to 1.

The following are the assumptions and scope of this research work.

1. Power supplies added or removed follow the power supply specifications given in Table 1. The differences between power supplies were expressed by varying their effective series resistances (ESR).
2. When reducing the number of available power supplies in the parallel configuration, the remaining active power supplies can still handle the given load current. Practically, a reduction in the number of active power supplies may mean total removal or failure of a power supply.
3. The efficiency of the parallel configuration will not be studied. When an actual hardware setup is to be implemented, a set of power supplies would simply be bought from one manufacturer. A future directive would allow to extend the study to a setup having power supplies from different manufacturers.
4. When using the fuzzy logic controller in [10, 11] in the scalable *n*-parallel configuration, the system still attains an equal power supply usage for each active power supply even if the added power supply was previously used. When compared to the standard practice of current sharing in power supplies, this research study proposes a novel control structure in determining the needed number of power supplies that can handle the required load. This approach is very advantageous to light loads where not all power supplies are

needed. The reduction of turned ON power supplies also reduces the power dissipation of such parallel configuration.

Since the parallel configuration of power supplies is scalable, one or more power supplies can be added or removed to/from the existing *n*-paralleled power supply modules. With the addition of power supplies, the fuzzy logic controller must take into consideration the total time of how long the previous power supplies were turned ON when new point of equal usage(s) is(are) determined.

The process of obtaining power supply usage is defined by Equation (5). In the simulation experiments, pulses were used to represent a second of simulation time. By dividing the number of pulses counted during the fraction of time the power supply is turned ON with the number of pulses for a whole duration of time t, the power supply usage can be obtained. Since rt can simply be cancelled out, the power supply usage (U_{conv}) is simply represented by the fraction of time the power supply is ON,

$$U_{conv} = \frac{frt}{rt} \times 100\% = f \times 100\% \tag{5}$$

where:

- f –fraction of time the power supply is turned ON
- r – rate equal to the number of pulses per second and is determined by the sampling time of the clock
- t – total time

When a power supply having a previous usage is added, its previous usage and previous run time must be taken into account.

First, consider static loading for any given parallel power supplies. Equation (3) simplifies to the expression below.

$$U_{conv} = \frac{1}{N} ceiling\left(\frac{I_x}{Io_{\max}}\right) \text{ x } 100\% \tag{6}$$

Using Equations (5) and (6) and given the previous power supply usage, (U_{prev}) as input and multiplying it with the rate and the previous run time, t_p, the number of pulses during the fraction of time the power supply is turned ON is obtained. The result is added to the product of variables $fr\Delta t$ which represents the number of pulses during the fraction of time the power supply will be turned ON. Δt represents the change in time after t_p. Therefore, Δt can be represented as $t_c - t_p$. The result is divided by the total number of pulses including the number of pulses previously counted. Since the variable r is present on both the numerator and denominator, it can be cancelled and the new power supply usage is given in Equation (7).

$$U_{conv} = \frac{1}{N} \times \frac{\frac{U_{prev}}{100} t_p + f\Delta t}{(t_p + \Delta t)} \times 100\% \tag{7}$$

where:

- t_p – added power supply's previous run time
- t_c – next simulation time
- $\Delta t = t_c - t_p$

In order to arrive at the percentage at which all power supplies will converge, the variable f must first be determined. In order to find f, multiple power supplies must be considered. When multiple power supplies are taken into consideration, multiple equations of (6) will be used by each power supply resulting to different values of f such as f_1, f_2, f_3, etc. It is possible to develop a relationship between the values of f by considering the number of required power supplies to turn ON under the assumption of static loading.

For example, a parallel configuration has four power supplies. The output current demand is 2A while each power supply has a maximum output current of 2.5A. All power supply usages will balance out at 25% usage each. Therefore, the fraction of time each power supply is turned ON is 0.25. It can be noticed that depending on the output current demand, Equation (8) is developed.

$$\begin{aligned} f_1 + f_2 + \cdots + f_N &= 1 \qquad I_o \le I_{o(\max)} \\ f_1 + f_2 + \cdots + f_N &= 2 \qquad I_{o(\max)} \le I_o \le 2I_{o(\max)} \end{aligned} \tag{8}$$

It can be noticed that the summation of all f_i, for $i=1,2,3,\ldots, N$ is related to the number of power supplies required to turn ON to support the output current demand. Taking into consideration multiple power supplies, the usage at which all power supplies will converge is described by Equation (9) below.

$$U_{conv} = \frac{1}{N} \times 100\% \left[\frac{\frac{t_p}{100}\left(U_{prev1} + \cdots + U_{prevN}\right)}{t_c} + \frac{\frac{t_p}{100}\left(f_1 + \cdots f_N\right)\left(t_c - t_p\right)}{t_c} \right] \tag{9}$$

Finally, Equations (6) and (9) can be combined to explicitly show the relationship between U_{conv} and the number of power supplies required to turn ON to support the output current demand in a scalable *n*-parallel power supply configuration. This is given by Equation (10) below.

$$U_{conv} = \frac{1}{N}\left[\frac{\left(\frac{Uprev1 + \cdots + Uprev_N}{100}\right)t_p}{t_c} + \frac{(t_p - t_c)ceiling\left(\frac{I_{out}}{I_{o(\max)}}\right)}{t_c}\right]\times 100\% \qquad (10)$$

3.0 RESULTS AND DISCUSSION

To verify Equation (10), a series of tests were done. It is easy to confirm that when adding new and unused power supplies, Equation (10) reduces to Equation (6).

The simulation experiment, its results presented in Figure 5, was done in static loading of 2A and in the following manner:

- From $t = 0$ to $t = 0.1s$, one power supply was simulated. Since there is only one power supply, power supply usage will simply be 100%.
- From $t = 0.1$s to $t = 0.3s$, another power supply was added. At this point, power supply 1 starts with a usage of 100% while power supply 2 has a usage of 0%. We use Equation (10) to determine their usages where they will be equal and get $U_{conv} = 50\%$
- From $t = 0.3$ to $t = 0.6s$, another power supply was added. Therefore power supplies 1 and 2 start with usages of 50%, with $t_p = 0.3$sec, and power supply 3 with a usage of 0%. It can be seen from Figure 5 that the three power supplies converged at t = 0.45s. Solving for U_{conv} at $t = 0.45s$, the power supplies converged at 33.33%.
- From $t = 0.6$ to $t = 1.0s$, another power supply was added. Therefore power supplies 1, 2 and 3 start with usages of 33.33% and power supply 4 with a usage of 0%. Taking into account the previous usages of power supplies 1, 2 and 3, the usage percentage converges at 25%.
- From $t = 1.0$ to $t = 1.375s$, another power supply was added. Therefore, power supplies 1, 2, 3 and 4 start with usages of 25% and power supply 5 with a usage of 0%. Taking into account the previous usages of power supply 1, 2, 3, and 4, the usage percentage where the five power supplies will converge is found to be 20%.

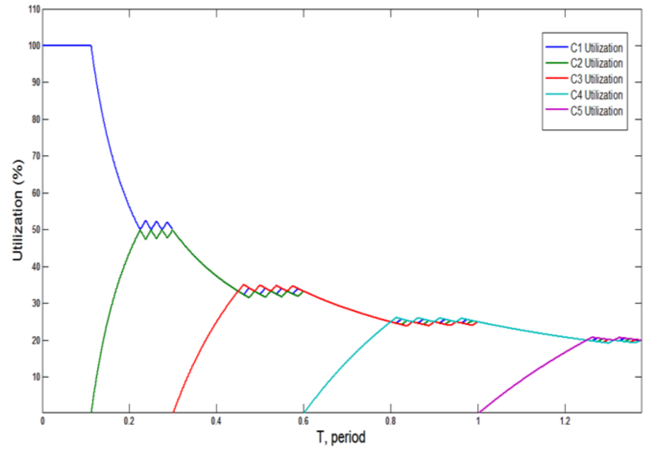


Figure 5 Power supply Usage under static loading of 2A, constant Vin with a single power supply starting from $t = 0s$ with additional power supplies added at $t = 0.1s$, $0.3s$, $0.6s$ and $1.0s$ respectively

There are some observations regarding Equation (10).

- The equation will only give the final value of the usage percentage that the active power supplies will converge to. It will not give the actual value of a power supply's current usage at a given time.
- It assumes that all active power supplies before addition and after removal have the same time of previous run time, t_p. If each power supply has its own previous run time, t_p, and power supply usage U_{conv}, then Equation (10) is extended into Equation (11). A sample simulation result is shown in Figure 6 and the corresponding voltage and current waveforms are illustrated in Figure 7. Since the required output load is only 2A, the fuzzy controller turns ON only ONE power converter at a time.

$$U_{conv} = \frac{1}{N}\left[\frac{\sum_{n=1}^{N}\left(\frac{U_{prevn}}{100}\right)t_{pn}}{t_c} + \frac{\sum_{n=1}^{N}(t_c - t_{pn})ceiling\left(\frac{I_{out}}{I_{o(\max)}}\right)}{t_c}\right]\times 100\% \qquad (11)$$

- For the scenario of adding new power supplies to existing parallel modules, it is obvious that the term $U_{prev1} + U_{prev2} + \cdots + U_{prevN} = 100$. Equation (10) reduces to (12) below

$$U_{conv} = \frac{1}{N}\times\frac{t_p + (t_c - t_p)ceiling\left(\frac{I_{out}}{I_{o(\max)}}\right)}{t_c}\times 100\% \qquad (12)$$

and will approach $U_{conv} = \frac{k}{N}\times 100\%,\ k = 1,2,3,\cdots,N$.

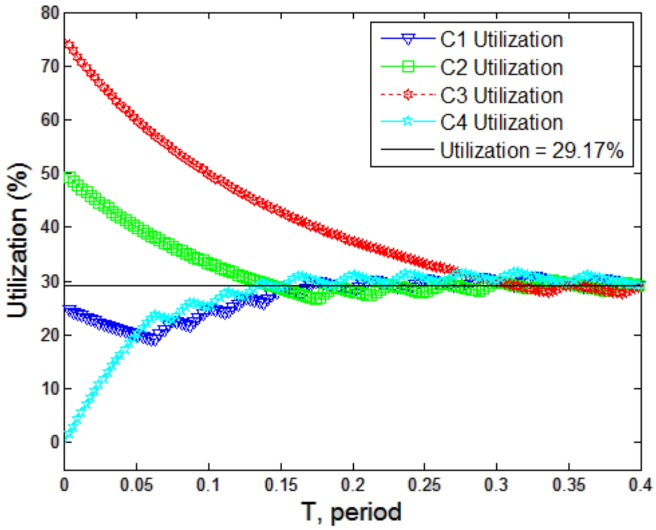


Figure 6 Power supply Usage under static loading of 2A, constant Vin with power supplies 1, 2, and 3 with previous usages of 25, 50, and 75% respectively

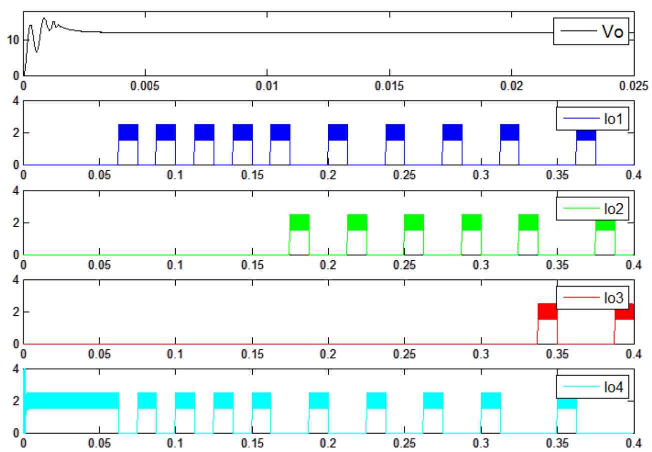


Figure 7 Corresponding output voltage and current sharing outputs, Iox under static loading of Itot = 2A constant Vin, with converters 1, 2, and 3 with previous utilizations of 25, 50, and 75% respectively

- For the scenario of removing power supplies from existing parallel modules, the term $U_{prev1} + U_{prev2} + \cdots + U_{prevN} < 100$, thus, the term $\frac{t_p}{100}\left(U_{prev1} + U_{prev2} + \cdots + U_{prevN}\right)$ will be less than 1. This setup will allow the active power supplies to equalize at higher power supply usage, since fewer power supplies are now sharing the required load. The fuzzy logic controller automatically knows the remaining power supply usage in the parallel configuration.
- The time t_c has value of $t_p < t_c \leq t_{stop}$, where t_{stop} is the stop time of simulation when a power supply was added or removed.

4.0 CONCLUSION

It was shown that the intelligent control using fuzzy logic for the *n*-paralleled power supplies was able to determine the number of power supplies to be turned ON or OFF given the output current requirement. It was also evident that the intelligent controller was able to balance the active power supplies' usage based on a power supply's current usage state and input voltage. Such controller was simulated in various static and dynamic loading tests and has shown promising results. Scalability was defined as the addition of new or removal of active power supplies from the parallel power supply configuration. The scalability issue was addressed through simulation by adding one power supply at a time and results shown that active power supplies still achieve an equalized value of power supply usage.

Finally, an expression relating scalability and usage percentage was derived and supported by simulation results. It is important to note that the developed expression can only be used to predict the value of usage percentage given a run time interval and not the actual value of how long a power supply is already running.

As a future directive for the proposed control structure, actual experiments will be done. The proposed fuzzy logic controller for equalizing converter usage time under various configurations will be implemented in a digital signal processor while the DC-DC buck converters will be bought off-the-shelf. The different simulation parameters presented in this paper will be derived empirically.

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