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Comparative study of various controllers applied to a three phases parallel multi-cell buck converter

***Abstract**. This paper presents a comparative evaluation study about the application of four control methods to a Parallel multilevel DC-DC converter, for purpose to achieve better currents and voltage regulation. Proportional-integral, Fractional Proportional-integral, Fuzzy logic and sliding mode controllers are applied. Fast dynamic response of the output current, voltage, and robustness to load variation are obtained with the sliding mode controller.*

***Streszczenie.** W artykule przedstawiono porównawcze badanie ewaluacyjne dotyczące zastosowania czterech metod sterowania do równoległego wielopoziomowego przekształtnika DC-DC w celu uzyskania lepszej regulacji prądów i napięć. Stosowane są sterowniki proporcjonalno-całkujące, ułamkowe proporcjonalno-całkowe, rozmyte i ślizgowe. Dzięki regulatorowi trybu ślizgowego uzyskuje się szybką dynamiczną odpowiedź prądu wyjściowego, napięcia i odporności na zmiany obciążenia. (**Badanie porównawcze różnych sterowników zastosowanych do trójfazowego równoległego wieloogniwowego konwertera buck**)*

Keywords: Parallel multicellular converter; PI controllers; Fuzzy Logic controller; Sliding Mode Controller.
Słowa kluczowe: przekształtnik DC-DC, sterowniki, sterowanie ślizgowe.

Introduction

Recent years have seen a growing interest in the parallel operation of DC-DC converters [1], mainly increasing the reliability, facilitating the maintenance system, ripple and system cost reductions. The parallel operation of power converters was first introduced in the inverter uninterruptible power system (UPS) [2], voltage regulator modules (VRM), for purposes of increasing output power capacity and system reliability [3]. A typical parallel multicellular chopper topology (PMC) will be studied [1], which is based on the combination of n identical switching cells, interconnected by means of inductances in order to absorb the instantaneous voltage between different cells [4, 5, 6].

Many controls are applied to regulate DC-DC converters, to achieve a robust output current and voltage [7], where the simple and low-cost controller structure is always in demand for most industrial and high-performance applications. Conventional control laws are very effective for linear systems with constant parameters. For non-linear parameters, these control laws may be insufficient because they are not robust especially when the requirements for accuracy and other dynamic features of the system are strict. Indeed, we have to use control laws insensitive to changes in parameters, disturbances and non-linearity [8]. Several control strategies and mathematical models have been developed by researchers [9,10].

Proportional-Integral (PIC), fractional proportional-Integral (FPIC), fuzzy logic (FLC) and sliding mode controllers (SMC) are four different control approaches considered for our DC–DC converter. The results of the four controls are applied to the PWM module. Then the resultant signals are applied to the switches [11]. The comparative study shows that the performances [12] using the sliding mode controller are slightly better than those obtained using a PI, FPI and fuzzy logic controllers. In fact, the output voltage and current responses show good rejections to the disturbance of load with good dynamics. Moreover, the chattering outputs and the transient overshoot in SMC are more than the other controllers [8, 11].

The paper is organized as follows: In section 2, the parallel multicellular converter modeling is presented. The comparative study of PI, FPI, fuzzy logic controllers and sliding mode, are tested in Section 3. The simulation results are presented in Section 4. Finally, a conclusion will be in the last Section.

MModelling of Parallel Multicellular Converter

The buck converter is one of the main part of many industrial applications. These converters are non-linear systems due to switching elements behavior [9, 10, 13].

In this paper, as it can be seen in Figure 1, a three parallel buck converter with resistive load will be studied [1, 5]. The binding inductances are identical on each cell and the physical switches are considered to be ideal. The input current for this converter is discontinuous, but the output is continuous because the output current is supplied by the output inductor/capacitor combination [9, 14].

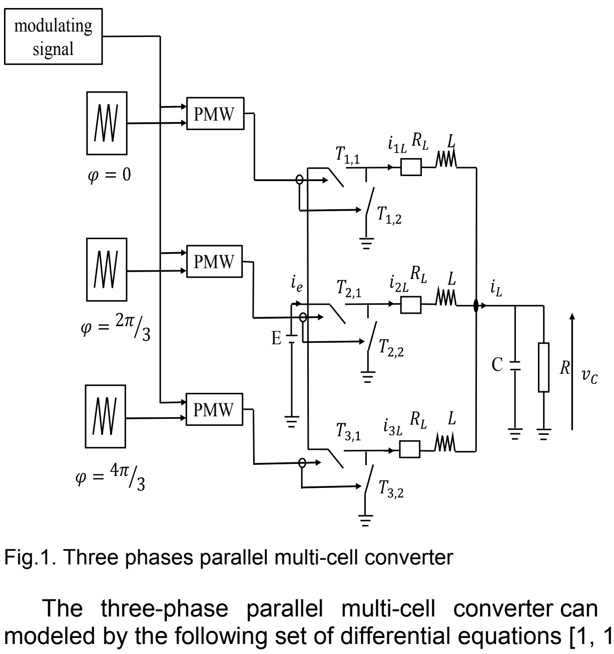

Fig.1. Three phases parallel multi-cell converter

The three-phase parallel multi-cell converter can be modeled by the following set of differential equations [1, 14]:

(1) $$\begin{cases} \dfrac{di_{1L}}{dt} = -\dfrac{R_L}{L} i_{1L} - \dfrac{v_c}{L} + S_1 \dfrac{E}{L} \\ \dfrac{di_{2L}}{dt} = -\dfrac{R_l}{L} i_{2L} - \dfrac{v_c}{L} + S_2 \dfrac{E}{L} \\ \dfrac{di_{3L}}{dt} = -\dfrac{R_l}{L} i_{3L} - \dfrac{v_c}{L} + S_3 \dfrac{E}{L} \\ \dfrac{dv_c}{dt} = \dfrac{1}{c}\left(i_{1L} + i_{2L} + i_{3L}\right) - \dfrac{v_c}{c_R} \end{cases}$$

Model (1) can be rewritten in the state form as below [4,14]:

(2) $$\dot{x} = f(x, q, t) = Ax + B(q)E$$

Where: $x = \left(i_{1L}, i_{2L}, i_{3L}, v_c\right) \in R^n$ is the continuous state, $q = \left(s_1, s_2, s_3\right)$ is the discrete input control. The dynamical matrix *A* and matrix *B*(*q*) are defined as:

(3) $$\begin{pmatrix} \dot{x}_{1L} \\ \dot{x}_{2L} \\ \dot{x}_{3L} \\ \dot{x}c \end{pmatrix} = \begin{pmatrix} -\dfrac{R_L}{L} & 0 & 0 & -\dfrac{1}{L} \\ 0 & -\dfrac{R_L}{L} & 0 & -\dfrac{1}{L} \\ 0 & 0 & -\dfrac{R_L}{L} & -\dfrac{1}{L} \\ \dfrac{1}{c} & \dfrac{1}{c} & \dfrac{1}{c} & \dfrac{1}{c} \end{pmatrix} \begin{pmatrix} x_{1L} \\ x_{2L} \\ x_{3L} \\ x_C \end{pmatrix} + \begin{pmatrix} s_1 \\ s_2 \\ s_3 \\ 0 \end{pmatrix} E$$

where: $$s = \begin{cases} 1, & s \quad closed \\ 0, & s \quad closed \end{cases}$$

x: circulating current through the three branch and the output voltage; *s*: control input, its value is expressed in terms of the switching function.

Closed Loop Control of Parallel Multicellular Converter

The main objective of most closed-loop feedback controlled DC/DC converters is to ensure that the converter operates with fast dynamical response, small steady-state output error, while maintaining high efficiency [15].

This converter has two stages namely, the power stage that is the buck and the control stage which is the PI, fractional PI, fuzzy, or sliding mode. The controller is a loop, which should be designed in such a way, that it makes changes in the power stage to make the output to quickly settle to the desired value |16]. Typically, the parallel multiphase buck converter has several paralleled power stages [13], with a current loop in each phase and a single voltage loop. The presence of the current loops avoids current imbalance among phases [1]. Each control method has its own advantages and drawbacks, however, it is always demanded to obtain a control method that has the best performances under any conditions [5, 16, 17].

For our work, we are going to do the study for one cell and it will be the same for the other two cells.

- **PI controllers**

An improved closed loop controller namely PI controller is proposed in this paper, as illustrated in figure 2 below

- **Traditional PI controller**

This converter is known to fail to perform satisfactorily under parameter variation, nonlinearity, or load disturbance. The PI controller is based on linear model [8], where we have a combination of an integral and proportional gain, as shown in figure 3. K_p is effective to reduce the step up time and the integral controller K_i,is effective to eliminate steady state error [18]. The output voltage of the buck converter is measured and compared with a reference voltage, the obtained error operates as an input in a suitably tuned PI controller in order to generate i_{lref}, which is in its turn compared with i_l to give an error which is introduced in a second suitably tuned PI to yield the duty ratio [8,19].

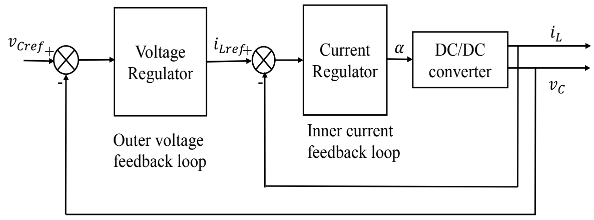

Fig.2. Proposed PI controller for Buck chopper

For the PI control design, it is essential to define the loop transfer function and the closed loop transfer functions for the output voltage and current [10,16,17].

The typical PI control law in its standard form is:

(4) $$u(t) = K_p e(t) + K_i \int e(t) dt$$

Where: $e(t) = y_{ref}(t) - y(t)$ is the system error (difference between the reference and measure value)

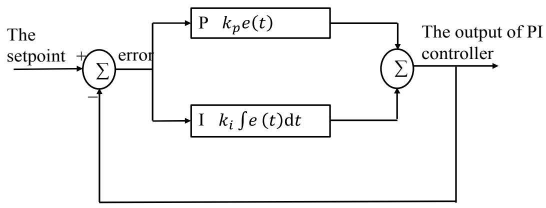

Fig.3. PI Controller

And the transfer function is given by:

(5) $$C(p) = K_p + \frac{K_i}{p} = \frac{1 + \tau p}{T_i p}$$

p : number of poles; T_i : integral time

For the voltage loop [9]: The transfer function giving the relation between the output voltage v_c and the current i_c , can be written as:

(6) $$TF_V = \frac{v_c(p)}{i_c(p)} = \frac{1}{cp}$$

And for the current loop: The relation between the inductance current i_L and its voltage v_L is:

(7) $$TF_C = \frac{i_l(p)}{v_l(p)} = \frac{1}{lp}$$

The transfer function of a closed loop system is given by:

(8) $$F(p) = \frac{\omega_0 (1 + \tau p)}{p^2 + 2\varepsilon_0 \omega_0 p + \omega_0^2}$$

By identification, for the voltage loop:

$$\omega_0 = \sqrt{\frac{K_i}{c}} \quad , \quad \varepsilon_0 = \frac{K_p}{2c\omega_0}$$

For the inner loop:

$$\omega_0 = \sqrt{\frac{K_i}{l}} \quad , \quad \varepsilon_0 = \frac{K_p}{2l\omega_0}$$

With: $K_p = \frac{\tau}{T_i} \quad K_i = \frac{1}{T_i} \quad \tau = \frac{K_p}{K_i}$

- **Fractional order PI controller**

Fractional order controller is widely used in most areas of science and engineering, being recognized its ability to yield a superior control in many dynamical systems. Due to the unwanted nonlinear characteristics, the converters require a controller with a high degree of dynamic response [22].

The most common form of a fractional order PI controller is the PI^{λ} controller involving an integrator of order *λ,* where *λ* can be any real number [22]. So by controlling the fractional integrator operator, one more freedom degree, will be added to K_p, and K_i variables [21].

The transfer function of such a controller has the form:

(9) $$C(p) = K_p + \frac{K_i}{p^{\lambda}} \quad (\lambda>0)$$

In the time domain, the relationship between the input *e(t)* and the output *u(t)* for such a controller is described by [20, 22]:

(10) $$u(t) = K_p e(t) + K_{i\,0} D_t^{-\lambda} e(t)$$

where the operator $D_t^{-\lambda}$ denotes the λ^{th} order integrator with the fixed lower terminal (initial time) 0 and the moving upper terminal *t*. Based on the Riemann–Liouville definition of fractional integration [20,21].

(11) $$u(t) = K_p e(t) + K_i \int_0^t \frac{(t-\tau)^{\lambda-1}}{\Gamma(\lambda)} e(\tau) d\tau$$

Γ: gamma function

A comparison of the second terms of PI and PI fractional reveals that, in the fractional PI control, the weighted error is integrated instead of the error value. In this weighted integration, at time *t*, $\frac{(t-\tau)^{\lambda-1}}{\Gamma(\lambda)}$ the function plays the role of weight function for integrating the error history $e(\tau)$, $\tau \in [0, t]$.

This controller can also called a proportional-weighted integral (PWI) controller, where the equation can be rewritten as below [20, 23]:

(12) $$u(t) = K_p e(t) + K_i \int_0^t w(t,\tau) e(\tau) d\tau$$

- **Fuzzy logic controller (FLC)**

FLC is an attractive choice when precise mathematical formulations are not possible; it can work with less precise inputs and doesn't need fast processors [8, 18]. The schematic diagram of a closed loop FLC of buck converter is shown in figure 4.

In the FLC, the choice of controller inputs and outputs depends on the type of the controlled system and the required outputs. The most popular controller inputs are error (*e*) and the rate of change of the error (*Δe*) [24].

The error *e* and its variation *Δe* for the output voltage and the output current are defined by [11, 16]:

(13) $$e(k) = v_{cref}(k) - v_c(k)$$
$$e(k) = i_{lref}(k) - i_l(k)$$
$$\Delta e(k) = e(k) - e(k-1)$$

The outputs of the fuzzy controller, are a current reference i_{Lref} and a duty cycle α [11]:

(14) $$i_{lref}(k) = i_{lref}(k-1) + G\Delta i_{lref}(k) + G_S e(k)$$
$$\alpha(k) = \alpha(k-1) + G\Delta\alpha(k) + G_S e(k)$$

k : time at which values are sampled.

The three gains G_e , $G_{\Delta e}$, *G* are designed to act in a comprehensive manner on the control surface by enlarging or reducing the area, while the gain G_s is added to ensure stability in the steady state and eliminate the static error. So we adjust these gains, in order to ensure stability and establish the desired dynamic and static performance [9,25].

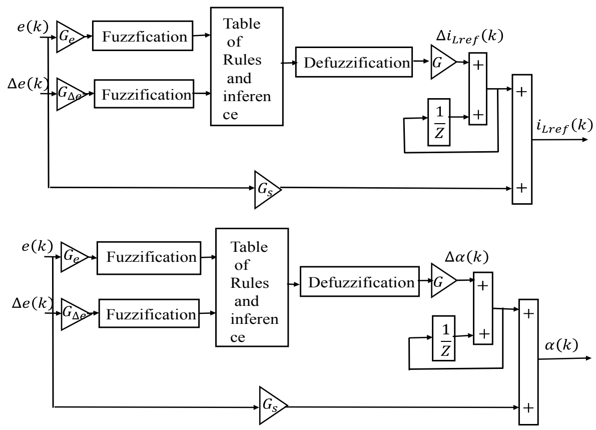

Fig.4. Model of fuzzy logic controller for output voltage and current

Figure 5 represents the membership functions for the error, change in error, and the output [9, 18].

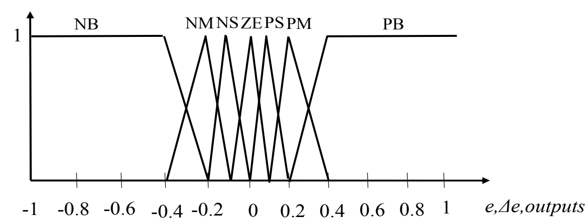

Fig.5. The membership functions

The structure of the fuzzy control rules is heuristic in nature and is based on the following criteria:

- The change of the two outputs of the controller must be large to bring the current and voltage to the set points quickly if the outputs of the converter are far from their references.
- A small change of the duty cycle and current reference are required if the outputs of the converter are approaching the set points.
- The current reference and the duty cycle does not need to change if the set points are reached and the outputs are steady

Fuzzy rules are gathered in an inference matrix shown in table 1.

Table 1. Rules of the Fuzzy Logic Controller

e¤ / Δe¤	NB¤	NM¤	NS¤	ZE¤	PS¤	PM¤	PB¤
NB¤	NB¤	NB¤	NB¤	NB¤	NM¤	NS¤	ZE¤
NM¤	NB¤	NB¤	NB¤	NM¤	NS¤	ZE¤	PS¤
NS¤	NB¤	NB¤	NS¤	NS¤	ZE¤	PS¤	PM¤
ZE¤	NB¤	NM¤	NS¤	ZE¤	PS¤	PM¤	PB¤
PS¤	NM¤	NM¤	ZE¤	PS¤	PM¤	PB¤	PB¤
PM¤	NS¤	ZE¤	PS¤	PM¤	PB¤	PB¤	PB¤
PB¤	ZE¤	PS¤	PM¤	PB¤	PB¤	PB¤	PB¤

NB: Negative Big; NM: Negative Medium; NS: Negative Small; ZE: Zero; PB: Positive Big; PM: Positive Medium; PS: Positive Small.

- **Sliding mode control (SMC)**

The SMC is naturally well suited for the control of variable structure system like DC-DC power converters [7]. So, it is appropriate to apply SM control on these power converters [10].

The sliding mode provides a method to design a system, which will be insensitive to parameter variations and external load disturbances [10, 26]. The main of this technique is to force the system states to the sliding surface, and the adopted control strategy must guarantee its trajectory to move toward and stay on the sliding surface from any initial condition [10, 17] as it is shown in figure 6 [27]. Moreover, this control offers excellent large-signal handling capability, which is important for variable structure systems [24], but the main problem when using this controller in case of DC/DC converters is the variable and high switching frequency, which increases losses [10].

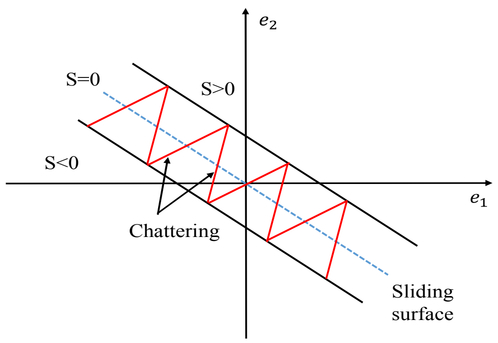

Fig.6. Sliding surface

In the present study, we define the sliding surface as follows [7]:

(15) $$S = e_1 - Ke_2$$

Where:

(16) $$e_1 = v_{cref} - v_c$$ $$e_2 = i_{lref} - i_{il}$$

(17) $$S = \left(v_{cref} - v_c\right) - K_1\left(i_{lref} - i_{1l}\right)$$

The inductor's reference current is generated via a traditional PI controller as:

(18) $$i_{lref} = K_P\left(v_{cref} - v_c\right) + K_I\int\left(v_{cref} - v_c\right)dt$$

After choosing the sliding surface, we must choose the control law to guarantee that the state trajectory of the system is directed to the sliding surface $S = 0$ and slides over it [8,17], where the reaching condition defined by Lyapunov equation as :

(19) $$V\left(x\right) = \frac{1}{2}s^2\left(x\right)$$

(20) $$\dot{V}(x) < 0 \Rightarrow s\,\dot{s} < 0$$

The control law is given as below:

(21) $$U = U_{eq} + U_{disc}$$ $$U_{disc} = -K.Sign\left(s\right)$$

U_{eq}: corresponds to the equivalent component, it is calculated from: $s = 0 \rightarrow \dot{s} = 0$

U_{disc}: corresponds to the nonlinear component. It must satisfy the condition of the convergence: s < 0, with K positive gain .

Figure 7 illustrates the application of each of the four controls for the three-cell chopper with same parameters for each cell and shifted by *2π/3*.

Simulation results

The proposed strategies are applied to the parallel multicellular Buck converter using MATLAB/SIMULINK environment. The parameters selected for this system are listed as shown in Table 2.

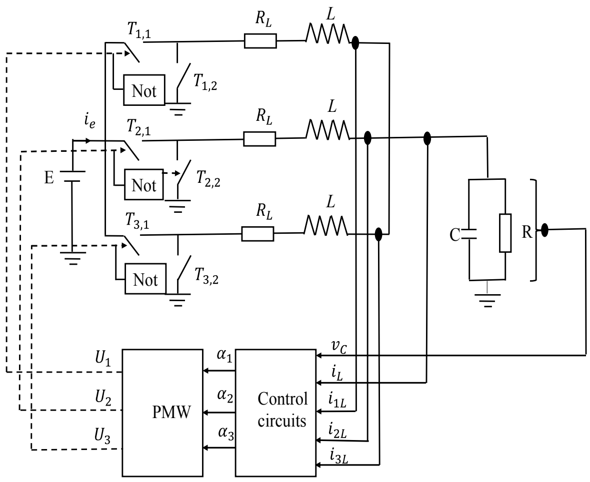

Fig.7. Multi-loop control for three parallel buck converter

The output voltage, current and phases current are simulated in transient state, steady state. In each case, a comparison between the four controls approache, PI, fractional PI, fuzzy and SMC are presented in table 3 to test their effectiveness without any disturbances.

Table 2. Converter's main circuit parameters

Parameter name	Symbol	Value
Input voltage	*E*	12 volts
Output voltage	V_C	6 volts
Inductor	*L*	100 μH
Inductor resistor	R_L	1 mΩ
Load resistance	*R*	0.6 Ω
Capacitor	*C*	100 μF
Switching frequency	*F*	100 kHz

The parameters of each regulator are given by:

PI controller:

K_p =0.5, K_i =10.10^3 (voltage regulation

K_p =10.10^3, K_i =10.10^3 (current regulation)

FPI controller:
K_p = 0.5, K_i = 11110, λ=0.9 (voltage regulation)
K_p = 100, K_i =1, λ=0.9 (current regulation)

FL controller:
G_e = 0.09 , $G_{\Delta e}$ = 9 , G = 0.09 G_s = 0.01 (voltage regulation)
G_e = 0.01 , $G_{\Delta e}$ = 0.1 , G = 0.9 G_s = 99 (current regulation)

SM controller:
K_1 =0.999 , K= 0.6

Figures 8, 9 and 10 present the output, voltage, current and phases current of DC/DC Buck converter with PI, FPI, FL and SM controls.

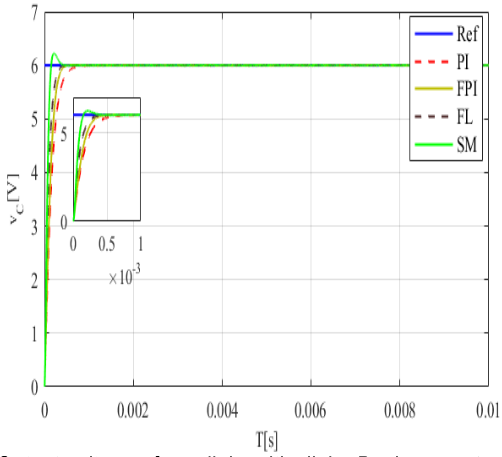

Fig.8. Output voltage of parallel multicellular Buck converter with the four controllers

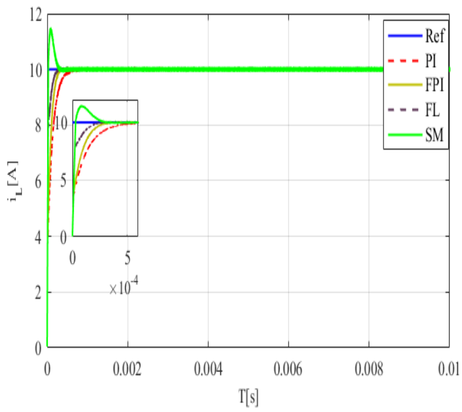

Fig.9.Output current of parallel multicellular Buck converter with the four controllers

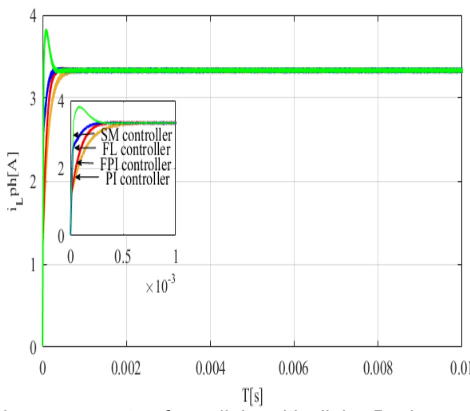

Fig.10.Phases currents of parallel multicellular Buck converter with the four controllers

In the transient region, the graphs 8,9,10 show that the settling time with traditional PI is longer than for the other studied techniques, and without overshoots. While the settling time with sliding mode is shorter, but on the other hand, the voltage and the currents present both an overshoot.

In steady state region as we can see from figures 11, 12 and 13, all the controllers have reached the desired value, however after comparing them, the output, voltage and currents ripples value differ from a strategy to another. We have a large output voltage and current ripples with sliding mode controller then the others, while the phases current ripples are bigger in case of fuzzy controller than the other three controllers.

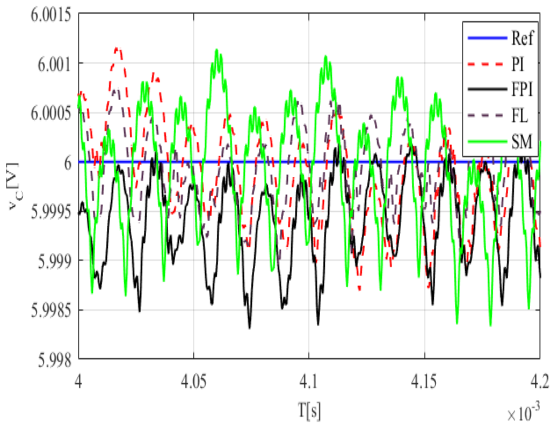

Fig.11. Output voltage ripple of Buck converter with each controllers in steady state

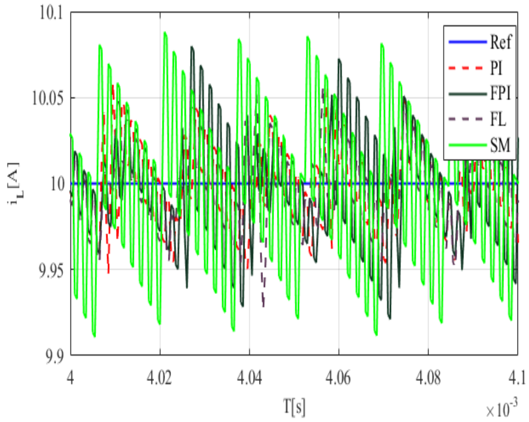

Fig.12. Output current ripple of Buck converter with each controllers in steady state

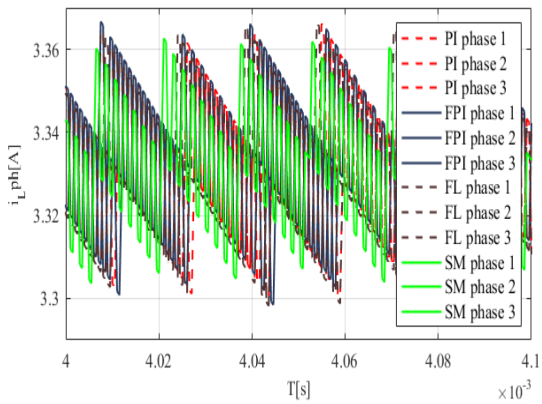

Fig.13. Phases current ripple of Buck converter with each controllers in steady state

Table 3. Comparison between the four models in transient and steady states

	PI control			FPI control			Fuzzy logic control			Sliding mode control		
	ST	MO	PP	ST	MO	PP	ST	MO	PP	ST	MO	PP
OV	0.7 ms	0	1.6 mV	0.5 ms	0	1.7 mV	0.44 ms	0	1.4 mV	0.4 ms	230 mV	2.5 mV
OC	0.6 ms	0	144 mA	0.4 ms	0	150 mA	0.35 ms	0	160 mA	0.3 ms	1500 mA	170 mA
PC	0.6 ms	0	65 mA	0.4 ms	0	64 mA	0.35 ms	0	70 mA	0.3 ms	480 mA	57 mA

OV: output voltage
OC: Output current
PC: Phases current
ST: Settling time
MO: Maximum overshoot
PP: peak-to-peak

Load variation: the profile of the load make in this section is given by figure 14:

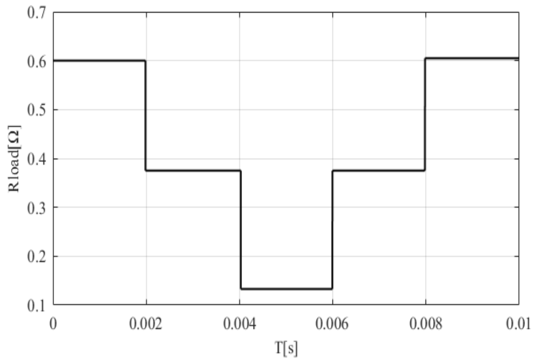

Fig.14. Load resistance variation graph

To test the robustness of the controllers against disturbances, the load is varied from designed value, from 0.6Ω to 0.37Ω, from 0.37Ω to 0.13Ω, then from 0.13Ω to 0.37Ω, and finally from 0.37Ω to 0.6Ω for every 2ms.

Figures 15, 16 and 17, give the output voltage, current and phases current of the DC/DC parallel multicellular Buck converter for the four controllers, when the load changes. As it can be noticed, the studied controllers provide all stable response.

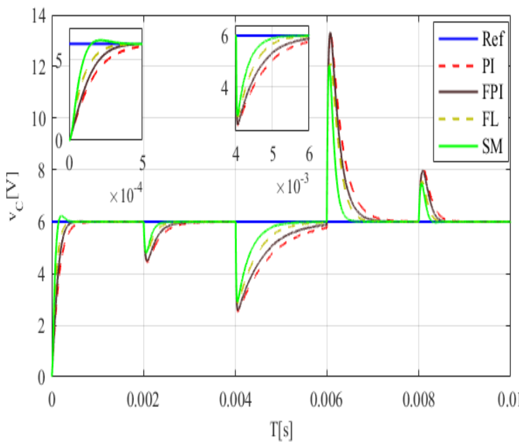

Fig.15. Dynamic responses of output voltage with changes in load using the controllers

changes, SMC responds in a highly damped manner whereas PI responds in an under damped one, in addition SMC shows a small overshoot.

We can notice that the converter behavior in transient and steady states under dynamic conditions is better when using SMC than in case

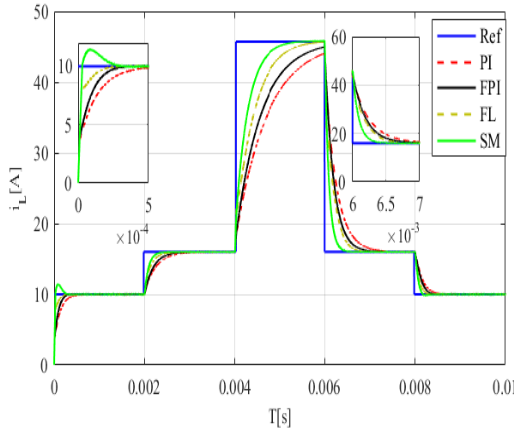

Fig.16. Dynamic responses of output current with changes in load using the controllers

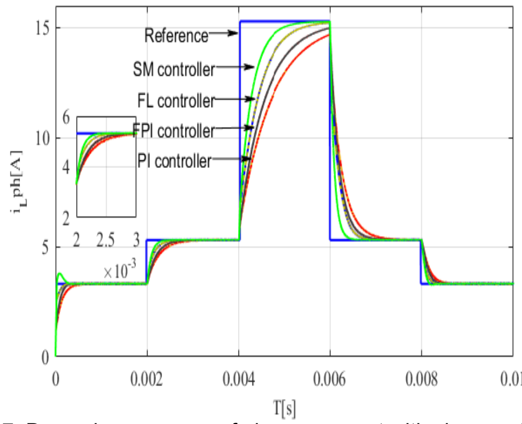

Fig.17. Dynamic responses of phases current with changes in load using the controllers

For load
of PI, FPI or fuzzy controllers.

Conclusion

This work presents performance comparison of classical controllers with modern controllers, applied for DC/DC multicellular parallel Buck converter. These regulators were tested in transient and steady states regions, and under load variation. PI controllers have a large transient response, where these constraints are overcame by SMC and FLC. Sliding mode controller emerges as a suitable control option for typical power supplies offering very fast response and good steady state characteristics. Even though the chattering output and the transient overshoot in SMC are more than for the other studied controllers. On the other hand, the PI and fuzzy controllers have a longer settling time without overshoot. Clearly, SMC has the best performance against disturbances.

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