Design and Simulation of the Auto-Tuning TS-Fuzzy PID Controller for the DC-DC ZETA Converter

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Abstract

In this paper, an auto-tuning fuzzy logic proportional integral derivative controller (ATFPID) based on a Takagi-Sugeno (TS) model for the DC-DC ZETA converter fed by a photovoltaic module is proposed. Having non-linear properties, ZETA converters with the classic linear proportional integral derivative (PID) controllers and fixed tuning parameters cannot demonstrate robust performance under the input voltage and load resistance variation. To tackle the problem, an adaptive fuzzy controller for each tuning parameter has been designed. The use of a Takagi-Sugeno fuzzy model compared to the famous Mamdani inference system is intended to ease the computational process. Performance analysis of both PID and TS-ATFPID controllers is carried out to evaluate output transient and steady-state responses of the converter using the fuzzy logic toolbox of the MATLAB/SIMULINK software. The results of the simulations demonstrate a significant performance improvement of TS-ATFPID over the conventional PID controller in terms of retaining output reference voltage under various stress levels and minimizing settling and rise time as well as the steady-state error and the overshoot.

Keywords

Fuzzy logic, PID controller, DC-DC power converter, ZETA converters

1. Introduction

With the rapid increase in demand for renewable energy sources, DC-DC converters have found considerable interest in a wide variety of applications, ranging from consumer electronics to photovoltaic systems (PV) [1, 2].

A ZETA converter is a special type of DC-DC converter which is similar to a single-ended primary inductor converter (SEPIC). One of the major similarities of these two converters is the non-inverted output voltage polarity, which is not the case in the popular buck-boost topology [3]. Another similarity is the ability of both regulators to output voltages with input voltages above or below the output voltage. However, in comparison with the SEPIC, a ZETA converter is based on a buck configuration [4].

In real applications with photovoltaic systems, a ZETA converter connects the photovoltaic module with the load. External factors such as solar irradiation and temperatures can have a significant negative impact on the output performance of the module, a problem of which can easily be tackled with the help of ZETA converters. Advancements in the control techniques of these converters are intended to improve the overall operational efficiency of the converters.

Traditional linear proportional integral derivative (PID) converters can be used to control the output of ZETA converters by changing the duty cycle applied to the switching element of the converter. However, optimal tuning of PID gains can be a challenging task, a problem of which can

ISIT 2021: II International Scientific and Practical Conference «Intellectual Systems and Information Technologies», September 13–19, 2021, Odesa, Ukraine
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be eliminated by introducing a fuzzy logic controller for each PID parameter to be tuned.

The main aim of the work is to design and simulate an adaptive fuzzy tuned PID controller for the ZETA converter to address tuning problems associated with the PID controllers and achieve increased robustness to the input and load disturbances. A Sugeno type inference system must be chosen for the fuzzy PID controller to alleviate the computational process as well as their ability to work with linear control methods.

2. System modeling

A ZETA converter and PID, TS-ATFPID controllers for the converter must be designed and simulated since the design and simulation of the controllers are crucial to assess their respective output performances and show superiority of the TS-ATFPID controllers.

2.1. ZETA converter modeling

The Simulink model of the ZETA converter operating in continuous conduction mode (CCM) is illustrated in Fig.1. In CCM mode, the inductor current never falls to zero, compared to the discontinuous conduction mode (DCM). A simple model of the ZETA converter involves two inductors (L1, L2), two capacitors (C1, C2), a diode (D), a metal oxide semiconductor field-effect transistor (M).

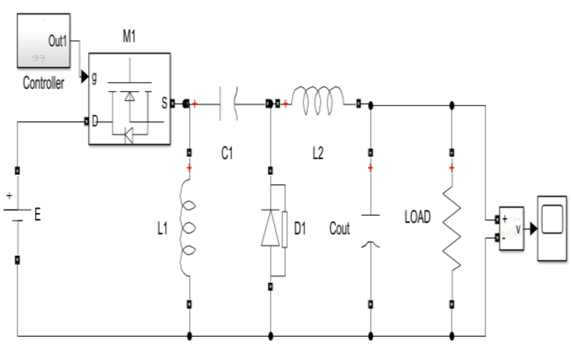

Figure 1: Simulink model of the ZETA converter

The converter operates on two modes;

In the first mode, MOSFET is switched on. The diode, D starts to be in its reverse-biasing mode, which involves the block of electrical current through it. The voltage across the inductor, L1 becomes equal to the supply voltage and the linear increase of the inductor current is also observed, as time passes. The capacitor, C1 commences charging to the output voltage

In the second mode, MOSFET is switched off. Since the polarity changes, the diode, D goes to the forward-biasing mode, in which electrical current can easily flow through it. Since, the current flows the diode, the inductor, L2 starts to be in parallel with the output capacitor, C_{out}. The capacitor, C1 discharges through the inductor, L1.

The simulation parameters of the designed Zeta converter is presented in Table 1.

A pulse-width modulation (PWM) based control mechanism is employed through the switching element of the converter, which is a MOSFET in our case, to regulate the output voltage of the ZETA converter.

Table 1
ZETA simulation parameters

Parameters	Nominal value
Supply voltage (E)	24 Volts
Input voltage variation	16-20 Volts
Input voltage variation	20-24 Volts
Capacitance (C1, C_{out})	19 mF
Inductors (L1, L2)	4 mH
Loads	35Ω/15Ω
Output reference	50 Volts

2.2. PID controller

To evaluate the improvements in the operational performance of the TS-ATFPID, a PID controller must be designed. PID controllers dominate the industry and are also considerably used in power electronics for the control circuit of the converters, due to their robustness, simple configuration, applicability in low-cost products.

Being composed of three simple proportional, integral and derivative terms, PID controllers have the following general mathematical representation:

$$u(t)=K_p e(t)+ K_i \int e(t)dt+K_d \frac{de(t)}{dt} \quad (1)$$

In the formula (1), u(t), e(t), K_p, K_i, K_d are the control signal, error, proportional coefficient, integral coefficient, derivative coefficient, respectively.

A Simulink model of the PID controller is shown in Fig.2.

A PID controller receives the error which is the difference between the reference voltage (V_{ref}) and actual output voltage (V_{actual}) and performs the relevant mathematical operations in a parallel configuration [5]. Each term of a PID controller plays an important role in improving the output response of the system.

The proportional term is intended to increase the speed of output response thereby decreasing rise time. However, as the error decreases, the effectiveness of the proportional term also reduces. Possible steady-state errors can be restricted to a tolerance level by introducing the integral term. The derivative term is considered anticipatory which operates on the rate of change of the error.

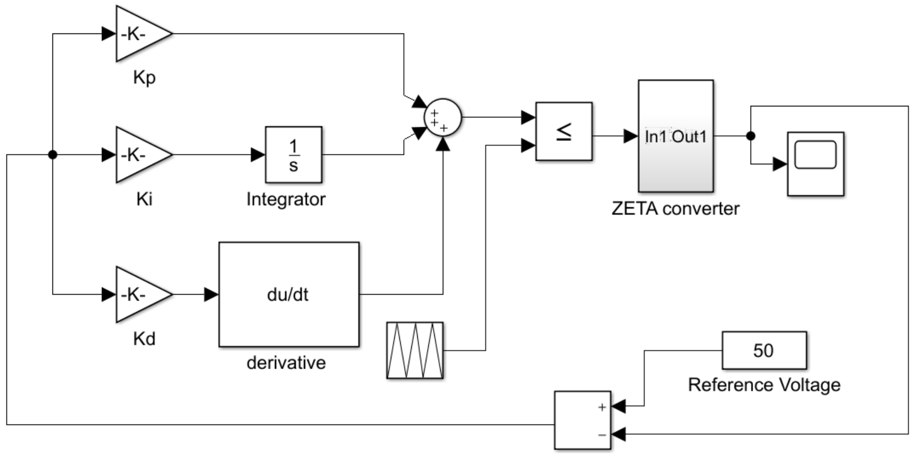

Figure 2: Simulink model of PID controller

Each coefficient of the relevant terms determines the strength of the terms, which requires to be optimally tuned.. The most popular traditional tuning method is the use of the Ziegler - Nichols method [6, 7].

In the design process of the PID controller, the Ziegler-Nichols method with the combination of trial-error methods has been employed. To implement this technique, first, all coefficients except for the proportional parameter is set to 0, after which the value of the proportional coefficient is increased until the system becomes unstable. The value of the proportional gain at the unstable state is recorded as K_{max}. The oscillation frequency of the system is denoted as f_0. The next stage involves the calculation process of the parameters.

Proportional, integral, derivative parameters can be calculated as $0.6K_{max}$, $2f_0$, $K_{max} \,/\, f_0$, respectively. Adopting this method, the coefficients of the PID controller are calculated as K_p=0.032, K_i =0.65 and K_d =0.18.

2.3. Fuzzy-PID controller

As is seen in the design process of the PID controller, one of the challenging tasks is the optimal tuning of the parameters. However, this problem can be tackled with the help of fuzzy logic controllers.

To design fuzzy controllers, the number of inputs must be selected and the conversion of these crisp input values to their corresponding fuzzy values with a certain range is needed. An increase in the number of inputs expands the fuzzy rule base, which increases processing power.

The error e(t) and the change in the error Δe(t) are selected as inputs for the fuzzy logic PID controller. For each input corresponding, 7 membership functions of Gaussian type are chosen.

The input space for e(t) and Δe(t) is defined to be in the interval of [-1,1] and [-0.001, 0.001], respectively and demonstrated in Fig.3 and Fig. 4.

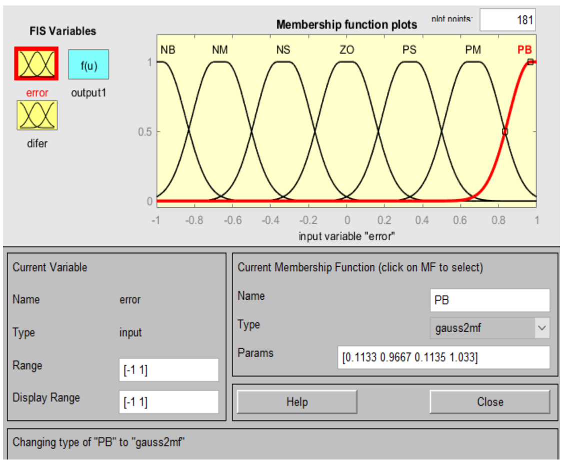

Figure 3: Membership functions for the error

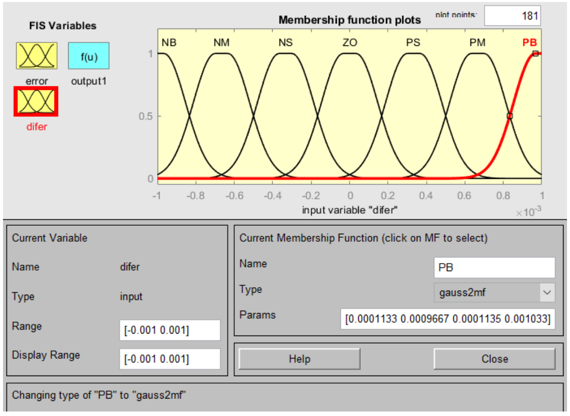

Figure 4: Membership for the change in error

The change in error $e(t)$ is determined by subtracting the previous output value of the error $e(t-1)$ from the actual value (3).

$$\mathrm{e(t)} = V_{ref} - V_{actual}, \tag{2}$$

$$\Delta\mathrm{e(t)} = e(t) - e(t-1). \tag{3}$$

The linguistic variables for the input are selected as negative big (NB), negative medium (NM), negative small (NS), zero (ZO), positive small (PS), positive medium (PM), positive big (PB).

A Takagi-Sugeno type inference system is preferred and chosen over the popular Mamdani model to ease the computational burden as well as ensuring compatibility with adaptive methods [8, 9].

The linguistic variables for output space are very small (VS), medium-small (MS), small (S), medium (M), big (B), medium-big (MB), very big (VB), each one of them corresponds to a specific linear function with the coefficients (*a*, *b*, *c*) being VS=[0.12 0.012 0], MS=[0.34 0.034 0], S=[0.45 0.044 0], M=[0.455 0.046 0], B=[0.76 0.037 0], MB=[0.83 0.047 0], VB=[0.93 0.047 0].

The rules of the presented TS type fuzzy logic controller has the following mathematical common form:

If input_1 is *e and* input_2 is Δe *then* output is

$$ae + b\Delta e + c \tag{4}$$

Table 2
The fuzzy logic rule-table for $\boldsymbol{K_p}$, $\boldsymbol{K_i}$, $\boldsymbol{K_d}$

e\Δe	NB	NM	NS	Z	PS	PM	PB
NB	VB/ VS /B	VB/ VS /B	MB/ VS /M	MB/MS/M	B/MS/M	M/M/VB	M/M/VB
NM	VB/ VS /S	VB/ VS /S	MB/MS/S	B/MS/S	B/S/M	M/M/S	S/M/MB
NS	MB/MS/ VS	MB/MS/ VS	MB/S/MS	B/S/S	M/M/M	S/B/B	S/B/MB
Z	MB/MS/ VS	MB/S/MS	B/S/S	M/M/S	S/B/M	MS/B/B	M/MB/MB
PS	B/S/ VS	B/S/MS	M/M/S	S/B/S	S/B/M	MS/MB/B	MS/MB/B
PM	B/M/MS	M/M/S	S/B/S	MS/MB/S	MS/MB/M	MS/VB/B	VS /VB/B
PB	M/M/B	M/M/M	MS/B/M	MS/MB/M	MS/VB/M	VS /VB/VB	VS /VB/VB

The fuzzy rule base is illustrated in Table 2. The designed TS-ATFPID controller is depicted in Fig.5.

3. Simulation Results

The performance of the controllers are tested under load and input variations and their relevant output responses are analyzed in terms of rise and settling time as well as the steady-state error and overshoot. The reference output voltage is selected to be 50 Volts (V).

In the first stage, output responses for the load resistance of 35Ω and 15Ω are plotted with the supply voltage of 24V and the reference voltage of 50V in Fig.6 and Fig.7, respectively.

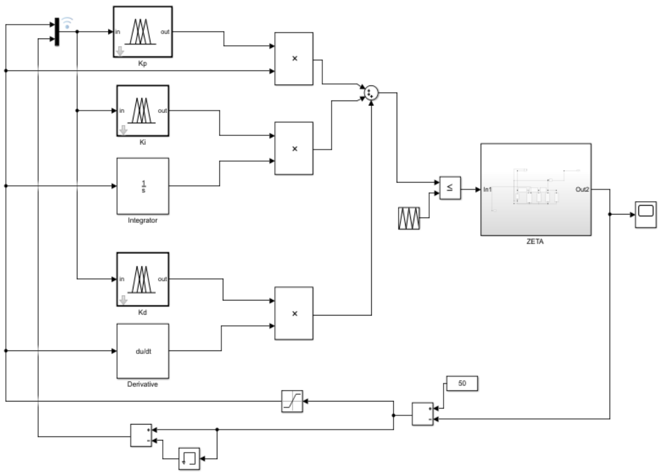

Figure 5: TS-ATFPIF controller for ZETA

In the second stage, the input voltage is varied from 20V to 24V and from 16V to 20V with the frequency of 200Hz and their relevant responses are shown in Fig.8 and Fig.9. Obtained numerical values are presented in Table 3 and Table 4.

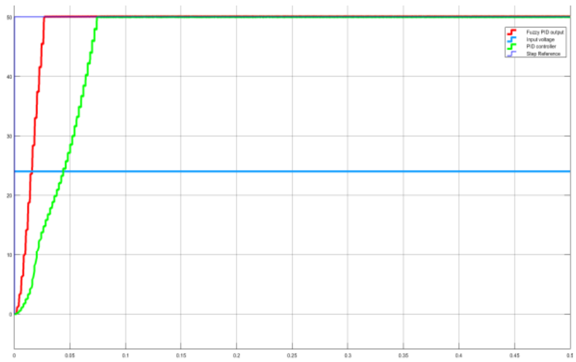

Figure 6: Output response (35Ω with 24V supply)

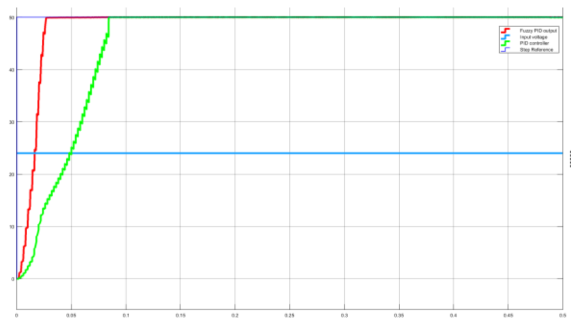

Figure 7: Output response (15Ω with 24V supply)

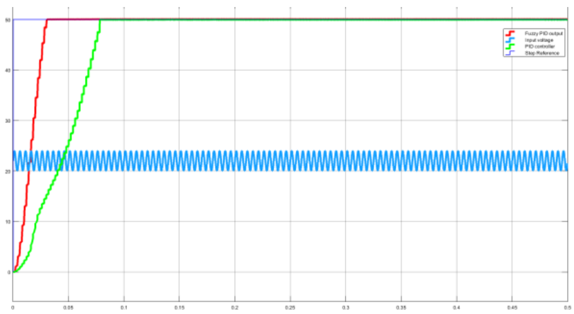

Figure 8: Output response (35Ω with 20-24V supply with 200Hz)

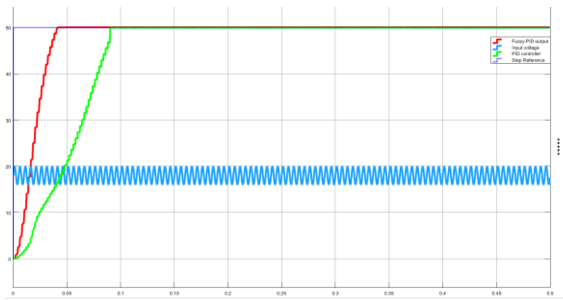

Figure 9: Output response (35Ω with 16-20V supply with 200Hz)

Table 3

Performance of controllers to load different load resistance

LOAD	BILEVEL MEASUREMENTS	ATFPID	PID
15 Ω	Rise time (ms)	28.262	84.608
	Settling time(ms)	28.860	85.934
	Overshoot (%)	0.358	0.502
	Steady-State error (V)	0.064	0.095
35 Ω	Rise time (ms)	27.427	74.967
	Settling time (ms)	27.838	80.236
	Overshoot (%)	0.347	0.506
	Steady-State error(V)	0.029	0.075

Table 4
Performance of controllers to input variation

Input variation	BILEVEL MEASUREMENTS	ATFPID	PID
20-24V 35 Ω 200 Hz	Rise time (ms)	32.081	77.759
	Settling time(ms)	32.360	78.234
	Overshoot (%)	0.388	0.505
	Steady-State error (V)	0.065	0.092
16-20V 35 Ω 200 Hz	Rise time (ms)	39.065	90.192
	Settling time(ms)	40.125	90.895
	Overshoot (%)	0.407	0.508
	Steady-State error (V)	0.068	0.071

4. Conclusions

An auto-tuning Takagi-Sugeno type fuzzy logic PID (TS-ATFPID) controller for ZETA converters has been proposed in this paper. The PID and TS-ATFPID controllers have been designed and simulated to assess their comparative performance. The simulations of the PID and TS-ATFPID controllers (TS-ATFPID and PID) are performed under load variations and supply voltage disturbances. The results of the simulations illustrate that under both conditions TS-ATFPID demonstrates superior transient and steady-state performance compared to the PID controller, thereby having substantially shorter settling and rise time as well as the steady-state error and overshoot.

5. References

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