

A Lyapunov-stable interval type-2 fuzzy PID controller design for ultra-lift Luo converter

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The ultra-lift Luo converter is a fourth-order DC-DC step-up converter capable of providing high voltage gain with low voltage and current ripples. However, its nonlinear dynamics, switching behaviour, and parametric uncertainties make controller design a challenging task. This paper proposes a Lyapunov-stable interval type-2 fuzzy PID controller for output voltage tracking of the ultra-lift Luo converter. The controller performance is investigated under step reference voltage changes, input voltage variations, and output capacitor uncertainties. A conventional PID controller is considered for comparison. Performance evaluation is carried out in terms of rise time, settling time, recovery time, overshoot/undershoot, and integral absolute error using a MATLAB/Simulink-based interval type-2 fuzzy logic toolbox. Simulation results demonstrate that the proposed controller achieves superior transient performance and provides enhanced robustness against parameter uncertainties compared with the conventional PID controller.

Keywords: ultra-lift Luo converter, Lyapunov stability, interval type-2 fuzzy PID controller

1 Introduction

DC-DC converters are power electronic devices that convert a given DC voltage level into another DC voltage level through high-frequency switching operation [1]. A high voltage transfer gain is essential for the efficient and reliable operation of power electronic systems. Such a high voltage conversion ratio can be achieved through the use of advanced converter topologies, such as Luo converters, which provide significant voltage boosting capability while maintaining low voltage and current ripples [2].

Among Luo converters, the ultra-lift Luo (ULL) converter is a novel topology developed based on the ultra-lift (UL) technique. Compared with other Luo converter families, such as voltage-lift and super-lift converters, the ULL converter provides a significantly higher voltage transfer gain, making it an attractive solution for high step-up voltage conversion applications. Furthermore, it offers improved power density, and enhanced efficiency under appropriate operating conditions [3].

The ULL converter poses a challenging control problem due to its inherent nonlinear characteristics, high-order dynamic behavior, and structural uncertainties. These features significantly complicate the controller design process and may adversely affect the stability, robustness, and dynamic performance of the ULL converter under varying operating conditions and parameter perturbations [4].

Conventional proportional-integral (PI), proportional-derivative (PD), and proportional-integral-derivative (PID) controllers are widely used in industrial applications due to their simple structure, ease of implementation, and satisfactory performance in controlling linear systems [5]. However, their effectiveness may deteriorate when applied to highly nonlinear and uncertain systems such as the ULL converter. To overcome these limitations and improve the performance of conventional controllers, many researchers [6-8] have integrated conventional control strategies with fuzzy logic controllers (FLCs). By combining the simplicity of PI, PD, or PID controllers with the intelligent decision-making capability of fuzzy logic, these hybrid control approaches can provide enhanced robustness, improved dynamic response, and better disturbance rejection in nonlinear and uncertain systems.

Although fuzzy PID controllers significantly improve system performance compared with their conventional counterparts, their effectiveness may be limited when the controlled system is subject to significant parametric uncertainties. In particular, classical or type-1 fuzzy logic controllers (T1FLCs) have a limited ability to directly represent and manage uncertainties arising from parameter variations. Type-1 fuzzy PID (T1FPID) controllers possess a simple control structure and can be analyzed using well-established theoretical frameworks [9]. However, their capability to maintain satisfactory

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control performance under substantial parametric uncertainties is often inadequate.

In the case of the ULL converter, the controller must accommodate large variations in input/output voltages and component parameters while ensuring closed-loop stability, robust operation, and fast transient response over a wide range of operating conditions.

Recently, considerable research efforts have been devoted to the control of ULL converters in existing literature. Various control strategies, ranging from conventional linear controllers to advanced intelligent and robust control techniques, have been proposed to enhance the dynamic performance, stability, and robustness of ULL converters under varying operating conditions and parameter uncertainties.

In [10], the authors designed a ULL converter for electric motor drive applications to regulate a constant output voltage using a PI controller. The findings demonstrated that the designed ULL converter achieved higher efficiency and lower voltage ripple than converters based on super-lift and voltage-lift techniques.

In [11], the authors proposed a type-2 fuzzy neural controller whose parameters were optimized using the firefly algorithm to enhance the dynamic performance of the ULL converter under varying operating conditions. The effectiveness of the proposed controller was evaluated through comparative simulations with conventional PI and fuzzy controllers. The results presented in [11] demonstrated that the proposed control strategy achieved superior transient and steady-state performance, thereby validating its effectiveness and robustness for ULL converter applications.

In [12], the authors investigated the stability characteristics of voltage-mode and peak current-mode controlled ULL converters. Furthermore, a hardware prototype was developed, and the effectiveness of the proposed converter was experimentally validated, demonstrating satisfactory dynamic performance and stable operation under different operating conditions.

In [13], the authors presented a novel hybrid approach to enhance the voltage transfer gain by integrating a ULL converter with a Cockcroft-Walton voltage multiplier for electric vehicle applications. The proposed approach was evaluated using MATLAB/Simulink simulations and compared with optimization-based methods, including the Billiards-Inspired optimization algorithm and the Giza Pyramids construction method. The results demonstrated that the presented hybrid topology achieved a higher voltage transfer gain, lower output voltage ripple, reduced voltage deviation, and smaller tracking error, thereby providing superior overall performance compared with the existing approaches.

In [14], the authors investigated three different current-mode control strategies for a high gain ULL converter, namely peak current mode control, average current mode control, and variable frequency hysteresis current mode control. To validate the ULL converter and control approaches, a hardware prototype was developed and experimentally tested. The comparative analysis revealed that the average current mode controller provided the best overall performance, exhibiting superior dynamic and steady state characteristics compared with the peak current mode and variable frequency hysteresis current-mode controllers.

In [15], the authors introduced a ULL converter capable of achieving a high output voltage gain that follows a geometric progression, thereby outperforming conventional voltage lift and super lift techniques. The effectiveness of the ULL converter was demonstrated through simulation studies. Furthermore, a PI controller was employed under various operating conditions, and the results showed satisfactory dynamic performance and effective output voltage regulation.

In [16], the author proposed a robust adaptive DC-voltage regulator for the ULL converter based on a PD-type interval type-2 Takagi-Sugeno-Kang (TSK) fuzzy controller. To evaluate its effectiveness, the proposed regulator was compared with a type-1 fuzzy controller. The comparative results demonstrated that the proposed interval type-2 fuzzy DC-voltage regulator significantly improved the output-voltage regulation performance of the ULL converter and provided more robust responses in the presence of uncertainties and varying dynamic operating conditions.

In [17], an ULL converter was proposed, and its dynamic performance was evaluated under both open-loop and PI controlled closed-loop conditions. Simulation results demonstrated the effect of duty cycle variation on the voltage transfer gain and verified the proposed converter model using MATLAB/Simulink.

Unlike the existing studies, this paper proposes a Lyapunov-stable interval type-2 fuzzy PID (IT2FPID) controller that combines the simplicity and effectiveness of the conventional PID controller with the uncertainty-handling capability of interval type-2 fuzzy logic. Owing to its interval type-2 fuzzy inference mechanism, the proposed controller can effectively cope with parametric uncertainties and nonlinearities while ensuring closed-loop stability through Lyapunov based design.

The major contributions of this paper to the existing literature can be summarized as follows:

- To the best of author's knowledge, a novel Lyapunov-stable IT2FPID controller is designed and applied to the ULL converter for the first time.

- The proposed Lyapunov-stable IT2FPID controller is developed to provide robust and fast output-voltage tracking performance in the presence of parameter uncertainties arising from input voltage variations, output voltage reference changes, and output capacitor variations.
- The proposed controller achieves superior dynamic output voltage tracking and disturbance rejection performance compared with the conventional PID controller in terms of rise time, settling time, recovery time, overshoot/undershoot, and integral absolute error (IAE).

The remainder of this paper is organized as follows. Section 2 presents the mathematical model of the ULL converter. Section 3 describes the design procedure of the proposed Lyapunov-stable IT2FPID controller in detail. Section 4 presents the simulation model and comparative studies conducted to validate the effectiveness of the proposed controller and evaluate its dynamic performance against the conventional PID controller. Finally, Section 5 summarizes the main conclusions and outlines future research directions.

2 ULL converter model

The ULL converter represents an advanced high step-up DC-DC converter topology developed to overcome the limitations of conventional Luo converters. Compared with the super-lift Luo converter [18], the ULL converter provides a higher voltage transfer gain, lower output voltage ripple, and improved conversion efficiency. By employing the UL technique based on geometric progression, the converter is capable of generating a significantly higher output voltage, making it attractive for applications requiring high voltage conversion ratios [19]. The circuit model of ULL converter is illustrated in Fig. 1.

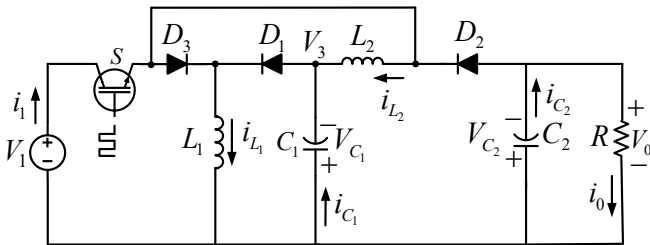


Fig. 1. Circuit model of ULL converter

As shown in Fig. 1, the circuit model of ULL converter consists of three diodes (D_1 , D_2 , and D_3), two inductors (L_1 and L_2), two capacitors (C_1 and C_2), switching element S , and load R . This circuit model generates an output voltage with a polarity opposite to

that of the input voltage. The relationship between the input voltage V_1 and the output voltage V_0 is expressed as:

$$V_0 = -\frac{D(2-D)}{(1-D)^2}V_1 \quad (1)$$

The duty cycle is represented by D , and the switching frequency is f . Therefore, the total switching period is $T=1/f$, with the switch-on duration being DT and the switch-off duration being $(1-D)T$. It is assumed that all elements, except the load R , are ideal, meaning that power losses during conversion are neglected. The ULL converter operates in two distinct modes, depending on the state of the switching element S under continuous conduction mode (CCM).

2.1 Switch on

When the switch is turned on, diodes D_1 and D_2 become reverse-biased and stop conducting, while diode D_3 becomes forward-biased and begins conduction. In this mode, the input voltage V_1 charges inductors L_1 and L_2 linearly, causing their currents to rise. At the same time, capacitor C_1 is charged by the current from inductor L_2 . The load receives a continuous current i_0 as capacitor C_2 discharges its stored energy to maintain a stable output.

2.2 Switch off

When the switch is turned off, diodes D_1 and D_2 shift to a forward-biased state and start conducting, while diode D_3 becomes reverse-biased and stops conduction. During this phase, the stored energy in inductors L_1 and L_2 is released, supplying both the load and capacitor C_2 . The discharge current from inductor L_1 flows through diode D_1 , while the current from inductor L_2 flows through diode D_2 . This process ensures a stable output voltage and uninterrupted load current, maintaining system stability [20]. Selected element values of ULL converter for simulation studies are given in Tab. 1.

Table 1. Selected element values of ULL converter

Parameter	Symbol	Value
Inductor	L_1	2 mH
Inductor	L_2	4 mH
Capacitor	C_1	5 μ F
Capacitor	C_2	5 μ F
Input Voltage	V_1	10 V
Output Voltage	V_0	-78 V
Load	R	6 k Ω
Switching frequency	f	50 kHz
Duty cycle	D	0.66

To ensure stable ULL converter operation and avoid impractical operating conditions, the duty cycle D is limited to the range of 0.1-0.95 throughout the analysis and simulations. To verify the selected component values of the ULL converter, the open-loop output voltage V_0 response of ULL converter with constant duty cycle 0.66 is presented in Fig. 2.

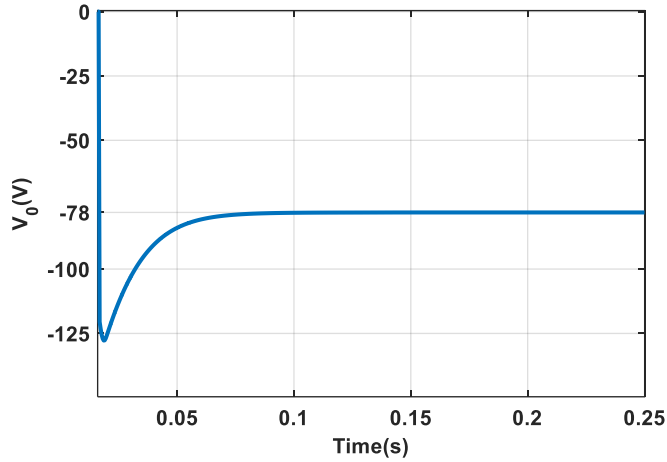


Fig. 2. Open-loop output voltage V_0 response of ULL converter with constant duty cycle (0.66)

For ULL converter design, the initial inductor currents and capacitor voltages were assumed to be zero. The converter output voltage V_0 was initialized at zero, while the duty cycle D was initialized at 0.66 and constrained within the range of 0.1-0.95.

3 Design of Lyapunov-stable IT2FPID controller

Type-2 fuzzy logic controller is a generalized version of type-1 fuzzy logic controller and it copes with numerical and linguistic uncertainties [21]. The memberships of a type-2 fuzzy logic controller are three-dimensional. In order to reduce the computational burden of type-2 fuzzy logic controller, interval type-2 fuzzy logic controller has been proposed [22]. An example of interval type-2 triangular fuzzy membership function is shown in Fig. 3.

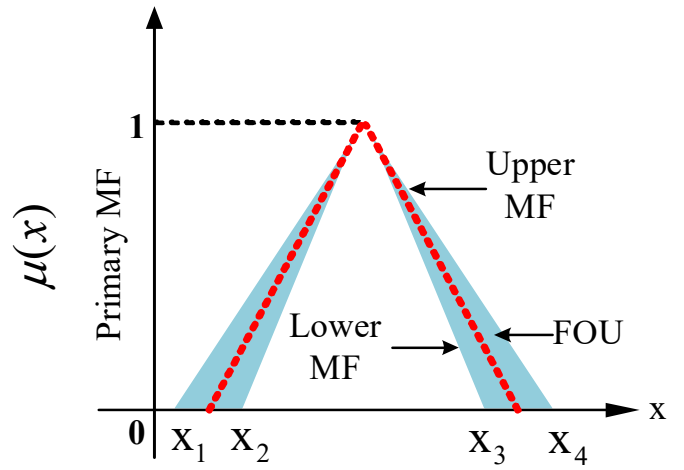


Fig. 3. Interval type-2 triangular fuzzy membership function

In this Fig. 3, it is considered that the grade of secondary membership is equal to one. So, there is no need to use the secondary membership function, as it does not change the value of the membership degree. Primary membership function has a mean and an uncertainty. This uncertainty is a bounded region between the upper and lower membership functions and it is known as footprint of uncertainty (FOU) [23]. A larger FOU indicates a higher degree of uncertainty, whereas a smaller FOU approaches the behavior of a conventional type-1 fuzzy set. Moreover, an interval type-2 fuzzy logic controller structure is shown in Fig. 4.

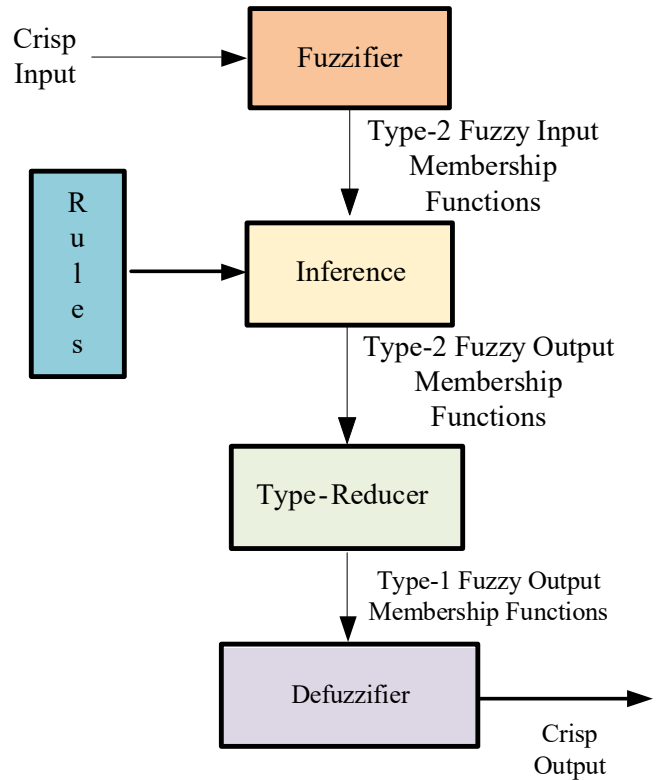


Fig. 4. Interval type-2 fuzzy logic controller structure

As shown in Fig. 4, crisp inputs are fuzzified with type-2 fuzzy input membership functions. After this process, the type-2 fuzzy input membership functions are created according to the input membership functions, membership degree, and fuzzy rule base. Crisp values of interval type-2 fuzzy logic controller were obtained after type reduction and defuzzification [24]. TSK inference model is used for interval type-2 fuzzy logic controller design. Antecedent parts of the interval type-2 fuzzy logic controller connect interval type-2 fuzzy membership functions with fixed means and uncertain standard deviation, and the consequent parameters have TSK type that realizes a linear function of input variables with type-1 fuzzy membership function. Each rule for interval type-2 TSK fuzzy logic controller is given as follows:

if x_1 is $\tilde{F}_1^i$ and ... x_j is $\tilde{F}_j^i$

$$\text{then } y^i = C_0^i + C_1^i x_1 + \dots + C_j^i x_j \quad (2)$$

Here, $i=1, \dots, M$, $x_1, \dots, x_n$ are inputs, $C_0^i, \dots, C_j^i$ are $n \times n$ dimensional matrices, including the consequent parameters of the output function y^i , y^i is the output function of the i^{th} rule and M is the number of rules, $\tilde{F}_j^i (j=1 \dots n)$ are type-2 fuzzy sets, and $\tilde{F}_j^i (j=1 \dots n)$ are type-1 fuzzy sets. The firing strength of the i^{th} rule $W^i(x)$ with meet operation under product or minimum t-norm is an interval type-1 set expressed as:

$$W^i(x) = [\underline{w}^i, \overline{w}^i(x)] \quad (3)$$

$$\underline{w}^i(x) = \underline{\mu}_{\tilde{F}_1^i}(x_1) * \dots * \underline{\mu}_{\tilde{F}_j^i}(x_j) \quad (4)$$

$$\overline{w}^i(x) = \overline{\mu}_{\tilde{F}_1^i}(x_1) * \dots * \overline{\mu}_{\tilde{F}_j^i}(x_j) \quad (5)$$

The procedure to compute final output can be performed using iterative Karnik-Mendel algorithm and is given as

$$[y_l, y_r] = \int_{w^l \in [\underline{w}^l, \overline{w}^l]} \dots \int_{w^M \in [\underline{w}^M, \overline{w}^M]} 1 / \frac{\sum_{i=1}^M w^i y^i}{\sum_{i=1}^M w^i} \quad (6)$$

Thus, for each rule, we obtain bounds y_l and y_r :

$$y_l = \frac{\sum_{i=1}^M w_l^i y_l^i}{\sum_{i=1}^M w_l^i} \quad (7)$$

$$y_r = \frac{\sum_{i=1}^M w_r^i y_r^i}{\sum_{i=1}^M w_r^i} \quad (8)$$

and the defuzzified output is [25]:

$$y = \frac{y_l + y_r}{2} \quad (9)$$

The IT2FPID controller is configured with two input variables and a single output variable. Its block diagram is shown in Fig. 5.

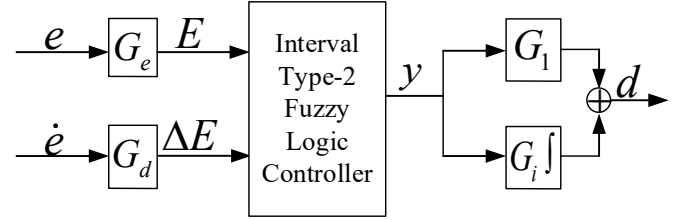


Fig. 5. Block diagram of IT2FPID

As shown in Fig. 5, IT2FPID is designed with choosing the two input variables as the error signal e and the derivative of error signal $\dot{e}$, while the output variable is the control signal d [26]. While G_e and G_d are the input normalization gains, G_1 and G_i are output normalization gains of PID. The control signal d applied to the ULL converter is given by:

$$d = G_1 y + G_i \int_0^t y dt \quad (10)$$

To reduce the computational complexity of the IT2FPID controller while preserving satisfactory control performance, a simplified MacVicar-Whelan rule base consisting of nine linguistic rules was employed. The IT2FPID controller uses two input variables, namely error e and derivative of error $\dot{e}$ each described by three linguistic terms: Negative (N), Zero (Z), and Positive (P). The output control action is determined according to the fuzzy rule base given in Tab. 2.

Table 2. General MacVicar-Whelan rule-base of IT2FPID controller

$e / \dot{e}$	N	Z	P
N	N	N	Z
Z	N	Z	P
P	Z	P	P

The simplified nine-rule fuzzy rule base provides a good compromise between computational efficiency and control performance. The input variables are described by identical interval type-2 triangular membership functions, as shown in Fig. 6, whereas the output variable is represented by type-1 fuzzy membership functions.

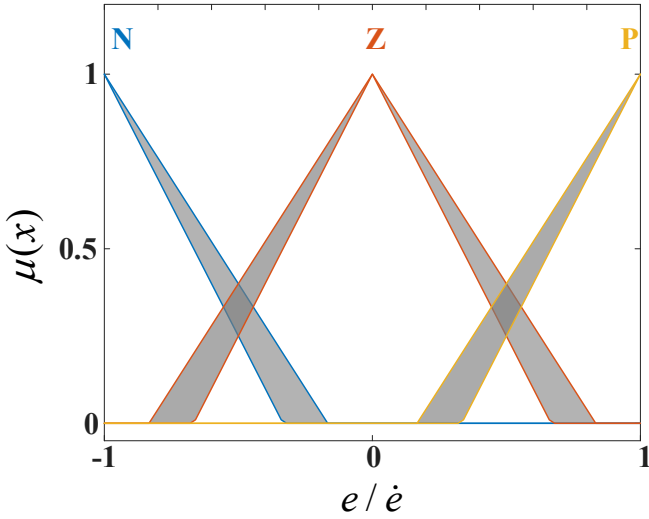


Fig. 6. Interval type-2 triangular fuzzy membership functions for input variables ($e / \dot{e}$)

For each input variable ($e / \dot{e}$), three interval type-2 triangular membership functions (N, Z, and P) with a 10% FOU were assigned interval $(-1, 1)$. Consequently, a compact nine-rule MacVicar-Whelan fuzzy inference system was obtained.

3.1 Stability analysis of IT2FPID

Stability is one of the most important issues in the design and analysis of control systems. It is quite difficult to analyze the stability of fuzzy control systems using non-linear stability theory since they are non-linear and have a rule-based structure. The specific requirements for a discrete-time fuzzy logic system are stated after the basic requirements of the Lyapunov stability theorem.

3.1.1 First theorem

$x(k) \in x_i$ and $f(\cdot)$ is a n -dimensional nonlinear function with the property $f(0) = 0$ for $\forall k$:

$$x[k+1] = f[x[k]] \quad (11)$$

Let's define $V[x[k]]$ as a scalar function with the following characteristics and examine a discrete-time system given by Eqn. (12):

$$\begin{aligned} i) & \quad V(0) = 0 \\ ii) & \quad V[x[k]] > 0 \quad \forall x[k] \neq 0 \\ iii) & \quad \|x(k)\| \rightarrow \infty \quad V[x[k]] \rightarrow \infty \\ iv) & \quad \Delta V[x[k]] < 0 \quad \forall x[k] \neq 0 \end{aligned} \quad (12)$$

The equilibrium point $x(k) = 0$ obtained by solving the equation $x[k] = f[x[k]]$ is globally and asymptotically stable for every k in this case, where $V[x[k]]$ is a Lyapunov function. This is the discrete version of the Lyapunov stability theorem.

3.1.2 Second theorem

$$x[k+1] = \frac{\sum_{j=1}^n f_j[x[k]] C_j x[k]}{\sum_{j=1}^n f_j[x[k]]} \quad (13)$$

The equilibrium point of the equation for the discrete IT2FPID controller can be described as follows:

$$C_j^T P C_j - P < 0 \quad \forall j = 1, 2, \dots, n \quad (14)$$

If a common strictly positive matrix P satisfies the criterion, it is asymptotically and globally stable. Let P be a $n \times n$ positive definite matrix, and let the scalar Lyapunov function be of the form $V[x[k]] = x^T[k] P x[k]$. This function satisfies properties (i), (ii), and (iii) in Eqn. (12). Let us examine whether it has the final property (iv):

$$\Delta V[x[k]] = x^T(k+1) P x(k+1) - x^T(k) P x(k) \quad (15)$$

Using Eqn. (15), the following expression is obtained:

$$\left[\frac{\sum_{j=1}^n f_j[x[k]] C_j x[k]}{\sum_{j=1}^n f_j[x[k]]} \right]^T P \left[\frac{\sum_{j=1}^n f_j[x[k]] C_j x[k]}{\sum_{j=1}^n f_j[x[k]]} \right] - x^T(k) P x(k) \quad (16)$$

Hence, $\Delta V[x[k]] < 0$ is obtained. According to the Lyapunov stability theorem, the discrete fuzzy system represented by Eqn. (13) is globally asymptotically stable [27].

4 Detailed simulation studies

This paper comparatively presents the output voltage tracking and disturbance rejection performance of the ULL converter using a Lyapunov-stable IT2FPID controller and a conventional PID controller. For this purpose, a simulation model of the output voltage tracking and disturbance rejection system was developed in MATLAB/Simulink using the free open-source interval type-2 fuzzy logic toolbox. The output voltage tracking structure of the ULL converter based on the Lyapunov-stable IT2FPID controller is shown in Fig. 7.

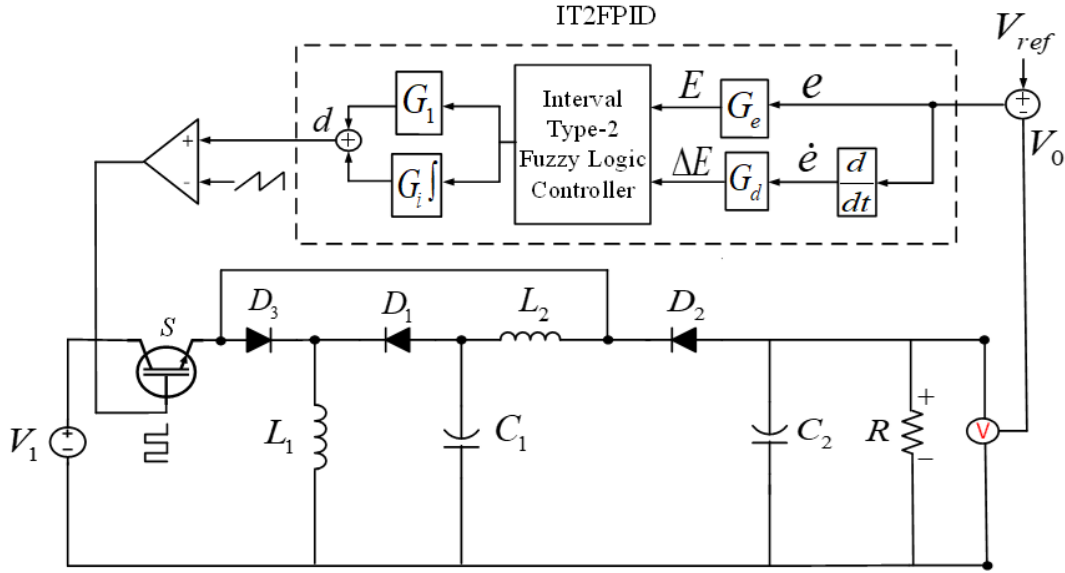


Fig. 7. Output voltage tracking structure of the ULL converter based on the Lyapunov-stable IT2FPID controller

It should be noted that the inputs and outputs of IT2FPID controller are occasionally defined in discrete time rather than continuous time. The following is how they are defined in discrete time:

$$e = V_{ref}[k] - V_0[k] \quad (17)$$

$$\dot{e} = \frac{de}{dt} \cong \frac{de}{T} \quad (18)$$

$$de = e[k] - e[k-1] \quad (19)$$

Here, the measurement output to the control scheme is V_0 , the reference input is V_{ref} , the sampling time is T , and e is difference between two and its derivative is $\dot{e}$. For all fuzzy controllers, the inputs in the discourse universe range are normalized using the normalization gains. For the error and derivative of error inputs, the input normalization gains are represented by the symbols G_e and G_d , respectively. The following is how the input normalization gains equalize the inputs:

$$E = G_e e \quad (20)$$

$$\Delta E = G_d \dot{e} \quad (21)$$

where the normalized derivative of error input is denoted by ΔE and the normalized error input by E . At the same time, the input normalization gains G_e and G_d are chosen to be 25 and 10, respectively, via trial and error to achieve the desired voltage tracking and disturbance rejection response. In addition, G_1 and G_i which are the output normalization gains, are selected as 100 and 1 to provide fast voltage tracking response, respectively.

Finally, the control signal of IT2FPID controller d is applied to the ULL converter's switching element S via PWM signal.

PID controller parameters were determined using the Ziegler-Nichols tuning method due to its simplicity and its ability to provide suitable controller gains without requiring an explicit mathematical model of the ULL converter. Since the ULL converter exhibits highly nonlinear characteristics and a high voltage conversion ratio, obtaining an accurate analytical model for controller tuning can be challenging. Therefore, the Ziegler-Nichols method was employed to obtain the initial controller parameters. The resulting gains (K_p , K_i and K_d) were subsequently refined through simulation studies to improve the output voltage tracking and disturbance rejection performance. The PID parameter tuning rules based on the Ziegler-Nichols method are presented in Tab. 3. The Ziegler-Nichols method is a widely used heuristic tuning technique for PID controllers. In this method, the integral and derivative gains are initially set to zero ($K_i = 0$ and $K_d = 0$). Subsequently, the proportional gain (K_p) is gradually increased from zero until the closed-loop system exhibits sustained and stable oscillations. The corresponding proportional gain is referred to as the ultimate gain K_u , while the oscillation period is called the ultimate period T_u . Once K_u and T_u are determined, the PID controller parameters can be calculated according to the tuning rules presented in Tab. 3. These parameters provide initial controller settings, which can be further refined to improve the dynamic and steady-state performance of the controlled system. The ultimate gain K_u is defined as $1/M$, where M is the amplitude ratio, $K_i = K_p/T_i$ and $K_d = K_p T_d$ [28].

Table 3. Ziegler-Nichols method

Controller	K_p	T_i	T_d	K_i	K_d
P	$0.5 K_u$	-	-	-	-
PI	$0.45 K_u$	$0.83 T_u$	-	$0.54 K_u/T_u$	-
PD	$0.8 K_u$	-	$0.125 T_u$	-	$0.1 K_u T_u$
PID	$0.6 K_u$	$0.5 T_u$	$0.125 T_u$	$1.2 K_u/T_u$	$0.075 K_u T_u$

After applying the Ziegler-Nichols method, PID parameters were further fine-tuned through simulation studies. The final gains were determined as $K_p=0.15$, $K_i=10$, and $K_d=50$, which provided the best trade-off between transient response and steady-state accuracy for ULL converter. Controller parameters used in this paper are summarized in Tab. 4.

Table 4. Controller parameters

Normalization gain	Value
G_e	25
G_d	10
G_i	100
G_i	1
PID gain	Value
K_p	0.15
K_i	10
K_d	50

Type-2 Fuzzy membership function settings	Value
Number of input and output fuzzy membership functions	3 (N, Z, P)
Input and output fuzzy membership function interval	$(-1, 1)$
FOU	10%
Number of rules	9

To evaluate the robustness of the proposed controller against parametric uncertainties, three different test scenarios were considered: step reference voltage

change, step input voltage change, and output capacitor C_2 variation. These scenarios are summarized as follows:

- Step reference voltage change: After the output voltage reached its steady-state value, the reference voltage was first changed from -78 V to -70 V and then from -70 V to -85 V.
- Step input voltage change: To investigate the effect of source voltage variations, the input voltage was increased from 10 V to 15 V and subsequently decreased from 15 V to 12 V.
- Output capacitor (C_2) variation: To assess the impact of parameter variations in the output stage, an additional $5 \mu\text{F}$ capacitor was connected in parallel with the output capacitor C_2 .

All simulation studies were performed in MATLAB/Simulink using a PC equipped with an Intel® Core™ i5 (11th Generation, 1.5 GHz) processor and 8 GB RAM. The simulations were carried out using the ode45 (Dormand-Prince) variable-step solver with a fixed simulation sampling time of $100 \mu\text{s}$ for the controller implementation.

4.1 Step reference voltage change scenario

In this sub-section, the set point voltage tracking performances of Lyapunov-stable IT2FPID and PID controller were tested under two step changes in the output voltage V_0 . In this regard, the step voltage response of commanded output voltage was decreased from -78 V to -70 V at $t=0.5$ s and increased from -70 V to -85 V at $t=1$ s, respectively. The total simulation time was 1.5 s. The set point voltage tracking and disturbance rejection performance of Lyapunov-stable IT2FPID and PID controller were compared in terms of their rise and settling time values. The comparative simulation results for the two step changes under the output voltage are shown in Fig. 8.

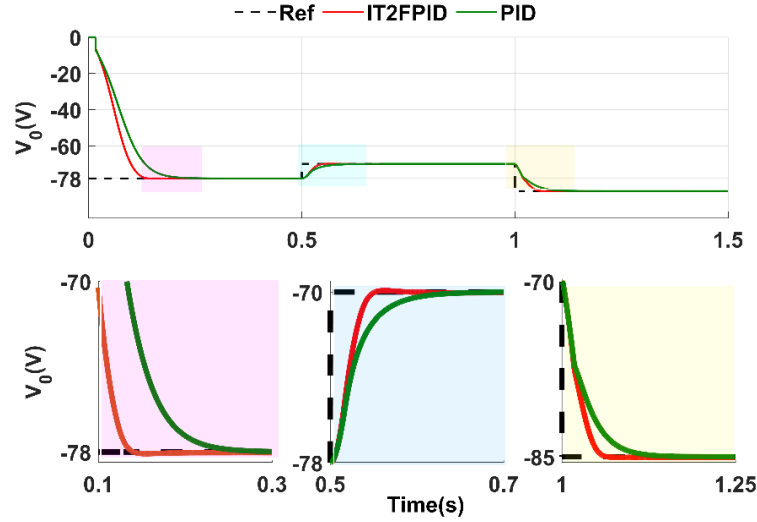


Fig. 8. Comparative simulation results for two step changes under the output voltage

When both controllers are compared in terms of their rise times, Lyapunov-stable IT2FPID controller provides the best result while PID controller has the worst result, which are 90 ms and 130 ms, respectively. For first and second step output voltage responses, the settling times of Lyapunov-stable IT2FPID controller and PID controller are calculated as being 125 ms and 150 ms, respectively. Moreover, both controllers ensure zero steady state error and achieve to keep the output voltage of ULL converter during steady states. At the same time, both controllers yielded no overshoots and undershoots. To demonstrate the performance of the Lyapunov-stable IT2FPID controller, the improvement percentages are calculated over the PID controller. When evaluated to the improvement percentages in rise times, Lyapunov-stable IT2FPID controller improved the performance of PID controller by 30.76%. When evaluated to improvement percentage in settling times for the first and second step responses, the Lyapunov-stable IT2FPID controller

improved the performance of PID controller by 16.66%. This improvement percentage shows that the Lyapunov-stable IT2FPID controller has a more satisfactory rise and settling time percentage than PID controller.

4.2 Step input voltage change scenario

This sub-section analyzed the set point voltage tracking performance of the Lyapunov-stable IT2FPID compared with the PID controller, under step input voltage V_1 changes. To this end, the input voltage V_1 was increased from 10 V to 15 V at 0.5 s and decreased from 15 V to 12 V at 1 s. The total simulation time lasted 1.5 s. The set point voltage tracking performance of Lyapunov-stable IT2FPID and PID controller are compared in terms of their recovery time, overshoot and/or undershoot values. Figure 9 shows comparative simulation results for the two step input voltage changes.

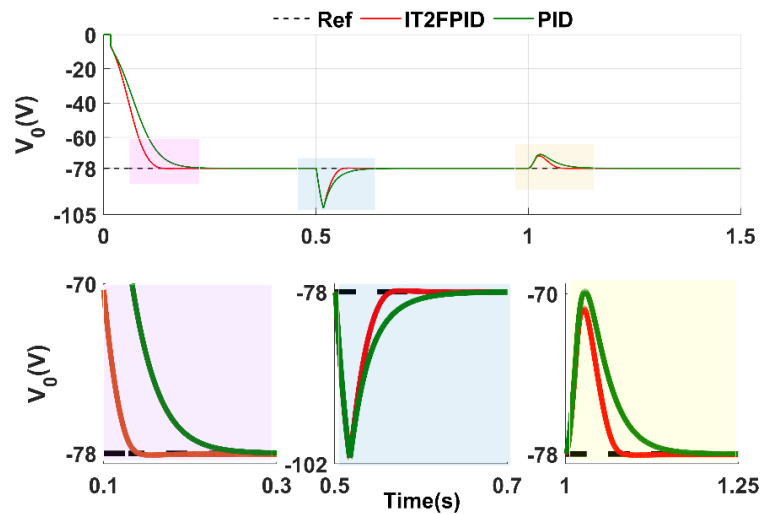


Fig. 9. Comparative simulation results for two step input voltage changes

When recovery time values of both controllers were evaluated for the first and second step input voltage changes, the recovery time values of the Lyapunov-stable IT2FPID controller and PID controller were obtained as 70 ms and 140 ms, respectively. Both controllers yielded same overshoot values are nearly 22.5 V during times of input voltage rise at 0.5 s. However, Lyapunov-stable IT2FPID controller and PID controller yielded different undershoot values are nearly 6 V and 8 V during times of input voltage drop at 1 s, respectively. At the same time, the improvement percentages are calculated over the PID controller to show the achievement of the Lyapunov-stable IT2FPID controller. Firstly, Lyapunov-stable IT2FPID controller improved the performance of PID controller by 50% with respect to recovery time values. Secondly, Lyapunov-stable IT2FPID controller improved the performance of PID controller by 25% with respect to undershoot values.

In addition, the improvement percentages of Lyapunov-stable IT2FPID controller showed quantitatively better transient performance compared to PID controller in terms of recovery time and undershoot values, despite the drop and rise in input voltage.

4.3 Output capacitor change scenario

This last sub-section tested the set point voltage tracking performance of the Lyapunov-stable IT2FPID compared with the PID controller, under output capacitor C_2 changes. In light of this, the output capacitor C_2 was increased from 5 μF to 10 μF at 0.5 s. The total simulation time was 1 second. The set point voltage tracking performance of Lyapunov-stable IT2FPID and PID controller are compared with respect to their integral absolute error values. Figure 10 shows comparative simulation results for the output capacitor C_2 changes.

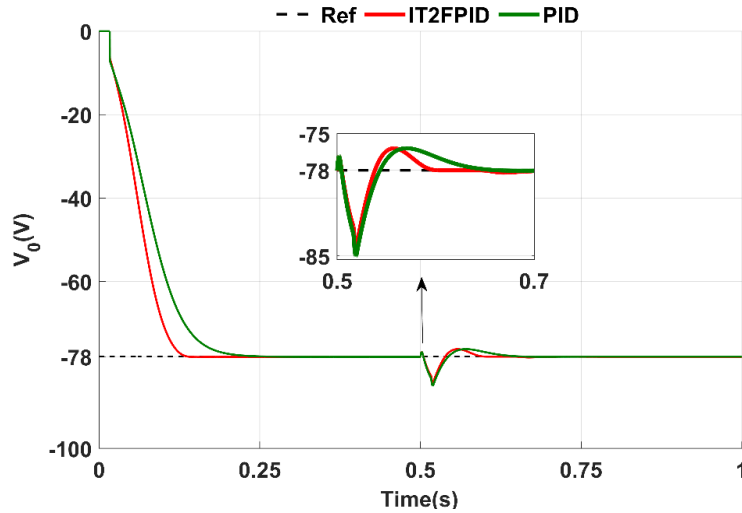


Fig. 10. Comparative simulation results for the output capacitor C_2 changes

As can be clearly seen in Fig. 10, both controllers yielded nearly the same undershoot and overshoot values of 1.8 V and 7 V, respectively, following the output capacitor C_2 change at $t = 0.5$ s. According to the existing literature, Integral Absolute Error (IAE) is a commonly used performance measure in control systems, especially for evaluating the quality of a controller in terms of how well it minimizes the error between the reference input and the measured output over time. The IAE for output voltage regulation of ULL converter is defined as:

$$IAE = \int_0^T |V_{ref}(t) - V_0(t)| dt \quad (22)$$

IAE helps to avoid excessive overshoot and steady-state error by minimizing cumulative deviation. The IAE values obtained for the Lyapunov-stable IT2FPID and PID controllers were 0.0542 and 0.0702, respectively. Based on the IAE criterion, the proposed Lyapunov-stable IT2FPID controller improved the control performance by 22.79% compared with PID controller. The improvement percentage obtained in this scenario quantitatively verified the superior performance of the Lyapunov-stable IT2FPID controller over the conventional PID controller. Finally, the control signal d for Lyapunov-stable IT2FPID and PID controller for this scenario were shown in Fig. 11.

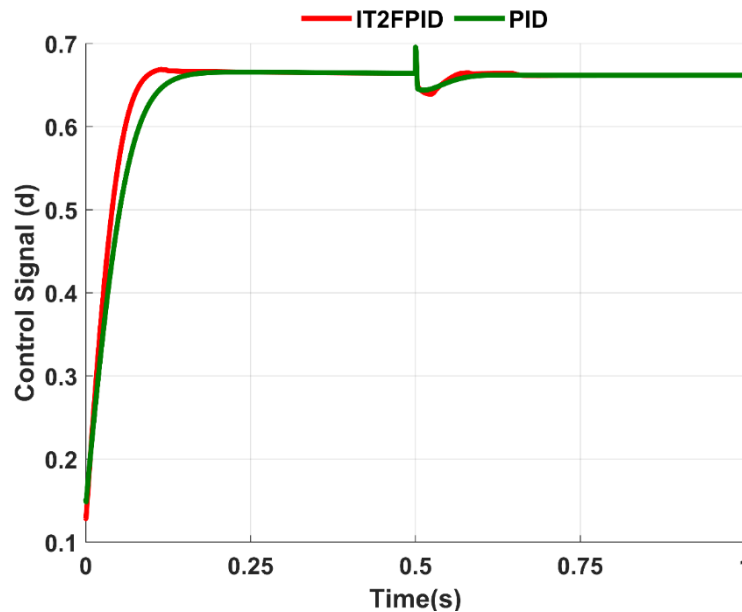


Fig. 11. Control signal d for the Lyapunov-stable IT2FPID and PID controller

5 Conclusion

This paper presented a novel Lyapunov-stable IT2FPID controller to regulate the output voltage of a ULL converter under different disturbance inputs. In order to evaluate the effectiveness of Lyapunov-stable IT2FPID controller, obtained results have been compared with PID controller. Based on the simulation results, the main findings can be summarized as follows:

- When the improvement percentages in rise and settling times are analyzed, Lyapunov-stable IT2FPID controller improved the performance of PID controller by 30.76% and 16.66%, respectively.
- For recovery time and undershoot, the improvement percentages for Lyapunov-stable IT2FPID controller are 50% and 25%, respectively.
- The improvement percentage achieved by the Lyapunov-stable IT2FPID controller in terms of IAE was 22.79%.

The obtained simulation results show that the proposed Lyapunov-stable IT2FPID controller outperforms the conventional PID controller in terms of all performance measures under all considered scenarios, except for overshoot. In future studies, it is planned to investigate the fault-resilient current control performance of a non-ideal ULL converter using type-2 fuzzy logic-based controllers and to compare their performance with that of their counterparts.

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