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- RESEARCH ARTICLE-

Dynamic Performance Evaluation of PI and Interval Type-2 Takagi-Sugeno-Kang Fuzzy Controller on Positive Output Luo Converter

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Abstract

Luo converter, a high voltage gain converter, shows a higher voltage gain and a lower output voltage ripple compared to conventional boost DC-DC converters. Luo converters perform voltage gain using a voltage lift method. Voltage gain is adjusted thanks to various circuit topologies using voltage lift method. Unlike linear circuit topologies, it is often difficult to model and control DC-DC converter circuits due to their switched structure. Conventional controllers such as PI, PD and PID remain inefficient in terms of controlling non-linear systems. Therefore, fuzzy logic based modern and intelligent controllers are needed with a view to improve the performance of non-linear systems. The present study proposes a PI and an Interval Type-2 Takagi-Sugeno-Kang Fuzzy Controller (IT2TSKFLC) for Luo converter with a positive output self-lift (POSLLC) circuit topology. MATLAB/Simulink was used to analyze the dynamic performance of these controllers.

Keywords:
Fuzzy Logic Control, Luo Converter

Introduction

Luo converters offer several advantages such as higher output voltage, higher power density, higher efficiency and lower output voltage ripples (Luo, 1999). Fuzzy logic (FL) can be defined as a set of rules which can be used to control mathematically undefinable complex systems. FL aims at transferring verbal expressions to the computer on the basis of mathematical expressions thanks to an expert’s experience (Acikgoz, 2018).

Introduced by L. Zadeh in 1975, Type-2 fuzzy logic controller (T2FLC) has been one of the most popular research topics in recent years (Zadeh, 1965). Because T2FLC shows a better performance in modelling uncertainties compared to Type 1 FLC (T1FLC), it yields betters results in controlling systems. T2FLC provides an efficient and adaptable control structure for a high controlling performance against system uncertainties. (Kumbasar, 2016).

The present study proposes an IT2TSKFLC, which is a special version of T2FLC, and a PI controller for the robust control of POSLLC. Section 2 POSLLC describes circuit structure and equations. Section 3 and 4 present IT2TSKFLC controlling system and PI controller, respectively. Section 5 discusses simulation studies. The conclusion section presents findings.

Material and Method

Positive Output Self Lift Luo Converter

Various circuit topologies using voltage lift technique can be found in the literatüre. Voltage lift technique eliminates effect of the parasitic elements, and thus offers a higher voltage gain and a lower output voltage ripple (Rashid, 2017). Positive output self-lift Luo converter (POSLLC) with a circuit topology is depicted in Figure 1.

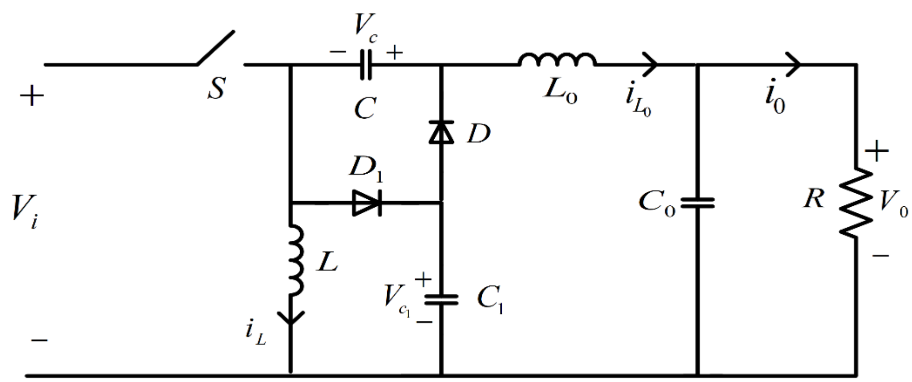

Figure 1. POSLLC circuit model

When S switch is closed, D_1 is forward biased whereas D diode is reverse biased. At a steady state, inductor voltages are zero for a certain period of time. During switch closed period, voltage in C_1 capacitor is equal to source voltage. In this situation, i_L inductor current increases whereas it starts to decrease during switch opened period. The equivalent circuit during switch closed period is shown in Figure 2.

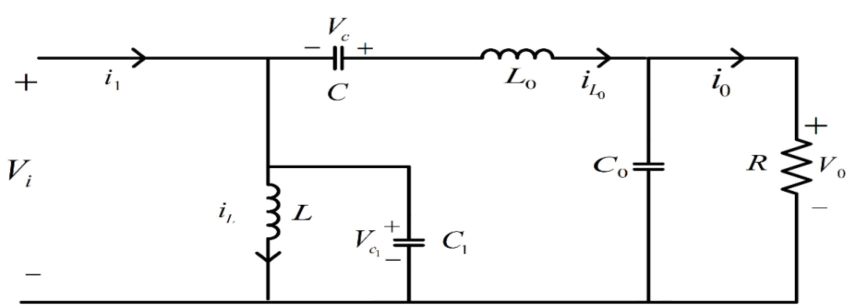

Figure 2. POSLLC equivalent circuit during switch closed period

Eq.1 can be written for the equivalent circuit during switch closed period.

$$V_0 = V_c = V_{c_1} = \frac{V_1}{1-k}$$
(1)

Because all components are ideal, power loss of circuit elements is neglected. Therefore, it is assumed that output power is considered as equal to the input power. When S switch is opened, D is forward biased whereas D_1 diode is reverse biased. The equivalent circuit during switch opened period is shown in Figure 3.

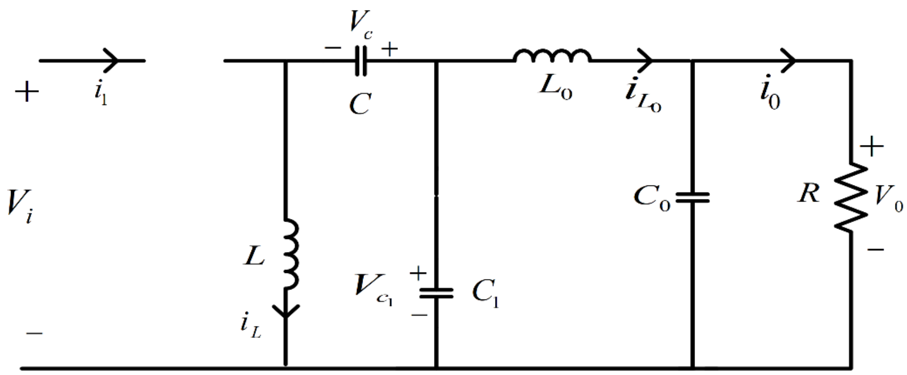

Figure 3. POSLLC equivalent circuit during switch opened period

During switch opened period, D diode is forward biased on and C capacitor is charged with input voltage (Chilambarasan et al., 2014). Eqs. 2-3 can be written for the equivalent circuit.

$$I_0 = I_L$$
(2)

$$I_1 = \frac{I_0}{1-k}$$
(3)

Interval Type 2 Takagi-Sugeno-Kang Fuzzy Logic Controller

In the design of T1FLC, the expert has to define the rules and parameters for the membership function. Uncertainties encountered in defining the rules may derive from the expert’s linguistic definitions. Problems may occur in defining the crisp values required for the membership function (Karanjkar, 2014).

These problems in T1FLCs may cause some instabilities such as measurement errors and changes in operating conditions of the controller. Furthermore, these unstable conditions can be considered as membership function uncertainties in IT2TSKFLCs. IT2TSKFLCs can eliminate adverse effects in instability conditions (Karnik et al.,1999). IT2TSKFLC consists of four main parts: fuzzifier, a rule base, a fuzzy inference, a type reducer, defuzzifier. The most important difference between IT2TSKFLC and T1FLC is type reduction. Type-2 information is converted to Type-1 information by means of the type reducer. The output of type-reduction block is called type-reducer. The type reducer is used for defuzzification process (Mendel et al.,2002). The internal structure of in IT2TSKFLC is shown in Figure 4.

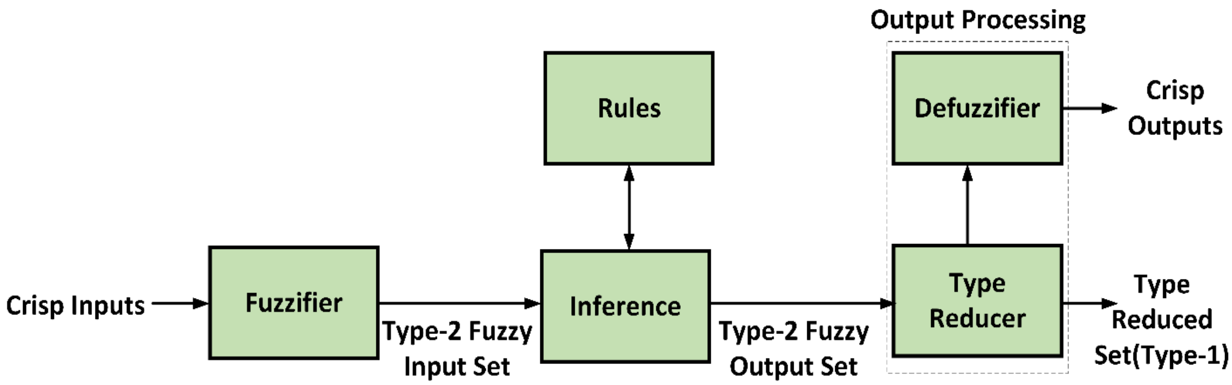

Figure 4.The internal structure of IT2TSKFLC

Introduced by Takagi, Sugeno and Kang, Takagi-Sugeno-Kang (TSK) is a fuzzy modelling method that comprises high dimensions,non-linearity and complexity (Takagi & Sugeno, 1985). An interval type-2 TSK model has a structure with two inputs and single output using rules given in Eq. 4. (Mendel, 2001):

$$R^k : IF\ x_1\ is\ \tilde{A}_1^{\,j}\ AND\ x_2\ is\ \tilde{A}_2^{\,n}\quad THEN\ LF_k = p_k x_1 + q_k x_2 + r_k \tag{4}$$

where k = 1,2,….,25 represents rule numbers; x_1, x_2 are input variables (e,de) ; $\tilde{A}_1^{\,j}$ and $\tilde{A}_2^{\,n}$ are membership functions; LF_k is the rule output; p_k , q_k , r_k are the consequent parameters. Gaussian type membership function is preferred in the present paper as shown in Figure 5. The mathematical equations for gaussian type membership function are given in Eqs. 5-6.

$$\overline{\mu}_{A_i^j}(x_i) = \exp\left\{-\frac{1}{2}\left(\frac{x_i - c_{ij}}{\overline{\sigma}_{ij}}\right)^2\right\} \tag{5}$$

$$\underline{\mu}_{A_i^j}(x_i) = \exp\left\{-\frac{1}{2}\left(\frac{x_i - c_{ij}}{\underline{\sigma}_{ij}}\right)^2\right\} \tag{6}$$

where $\mu_{\tilde{A}_i^j}(x_i)$ denotes the degree of membership for input variable, c_{ij} represents the mean value of function, σ_{ij} is standard deviation and x_i is the input variable.

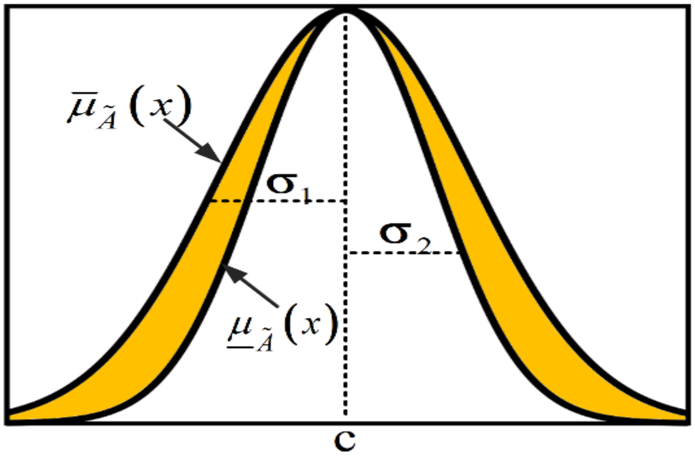

Figure 5. Gaussian type-2 fuzzy set

The firing strengths of the fuzzy rules are defined as lower and upper using product operator in Eqs. 7-8, respectively.

$$\overline{f}_{(n-1)\times J+j} = \overline{\mu}_{A_1^j}(x_1) * \overline{\mu}_{A_2^n}(x_2) \quad n=1,2,\ldots,N \ \ and \ \ k=(n-1)\times J+j \tag{7}$$

$$\underline{f}_{(n-1)\times J+j} = \underline{\mu}_{A_1^j}(x_1) * \underline{\mu}_{A_2^n}(x_2) \quad n=1,2,\ldots,N \ and \ k=(n-1)\times J+j \tag{8}$$

Normalization is performed by proportioning the firing strength of each node rule with the sum of the firing strengths of all rules. The normalization process is defined as follows:

$$\overline{F}_k = \frac{\overline{f}_k}{\sum \overline{f}_k} \qquad k=1,2,\ldots,25 \tag{9}$$

$$\underline{F}_k = \frac{\underline{f}_k}{\sum \underline{f}_k} \qquad k=1,2,\ldots,25 \tag{10}$$

Biglarbegian-Melek-Mendel (BMM) method is a closed-form type reduction and defuzzification method.(Biglarbegian et al., 2010).Closed mathematical form of type reduction and defuzzification process for the proposed IT2TSKFLC is calculated Eq.11.

$$Y_{BMM} = m\frac{\sum_{k=1}^{25} \overline{f}_k \overline{LF}_k}{\sum_{k=1}^{25} \overline{f}_k} + (1-m)\frac{\sum_{k=1}^{25} \underline{f}_k \underline{LF}_k}{\sum_{k=1}^{25} \underline{f}_k} \tag{11}$$

PI Controller

PI controller is widely used by researchers due to its easy structure. Generally, the output of a classical PI controller is represented by Eq.12.

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt \tag{12}$$

In the present study, Ziegler–Nichols method is used to tune the gain coefficients of the PI controller.From Ziegler–Nichols method, the gain coefficients Kp and Ki of the controller are finded as 0.001 and 5 for the POSLLC converter, respectively.

Results

Simulation Studies

IT2TSKFLC designed in the present study have two inputs and a single output. The inputs are the error (e) and change of error (de).Gaussian membership functions were selected for each input as shown in Figure 6.

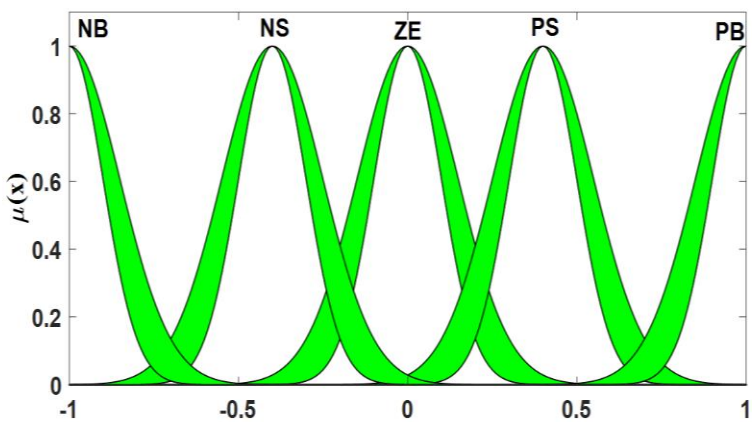

Figure 6. Gaussian membership functions selected for the error and change of error

A value range of [-1, 1] was set for Gaussian membership functions. Linguistic variables were selected as Negative Big (NB), Positive Big (PB), ZE (S), Negative Small (NS), Positive Small (PS). In addition, a rule base of 25 rules consisting of these linguistic variables are presented in Table 1.

Table 1. 5x5 rule base

x_2(de) / x_1(e)	NB	NS	ZE	PS	PB
NB	**LF_1**	**LF_2**	**LF_1**	**LF_1**	**LF_5**
NS	**LF_6**	**LF_7**	**LF_8**	**LF_9**	**LF_{10}**
ZE	**LF_{11}**	**LF_{12}**	**LF_{13}**	**LF_{14}**	**LF_{15}**
PS	**LF_{16}**	**LF_{17}**	**LF_{18}**	**LF_{19}**	**LF_{20}**
PB	**LF_{21}**	**LF_{22}**	**LF_{23}**	**LF_{24}**	**LF_{25}**

In the analysis of POSLLC, boundary values of proposed converter were calculated using Eqs. 13-17 based on the variation ratios of inductor currents and variation ratios of capacitor voltages.

$$\zeta_1 = \frac{R}{2M^2 fL}$$
(13)

$$\zeta_2 = \frac{kR}{2MfL_0}$$
(14)

$$\rho = \frac{k}{2fCR}$$
(15)

$$\sigma_1 = \frac{M}{2fC_1R}$$
(16)

$$\varepsilon = \frac{k}{8Mf^2 L_0 C_0}$$
(17)

Continuous current mode (CCM) is a steady state mode for converter circuits. Voltage gain in POSLLC for CCM is given in Eq. 18.

$$M = \frac{V_0}{V_i} = \frac{1}{1-k}$$
(18)

k in Eq. 18 represents the duty cycle of POSLLC. The calculated boundary values for CCM in POSLLC are given in Table 2.

Table 2. Boundary values for POSLLC

V_i	20 V	L	1.1 mH
V_0	60 V	C_o	8 uF
R	100 Ω	C	10.67 uF
k	0.67	C_1	12 uF
L_0	2.2 mH	f	50 Khz
M	3	ζ_1	0.1
ζ_2	0.1	ρ	0.00625
σ_1	0.025	ε	0.000625

Real converter values should be selected higher than boundary values for CCM. The selected converter parameters for simulation studies are given in Table 3.

Table 3. Selected values for POSLLC

V_i	20 V	L	10 mH
V_0	60 V	C_o	100 uF
R	100 Ω	C	100 uF
k	0.67	C_1	100 uF
L_0	10 mH	f	50 Khz
M	3	ζ_1	0.1
ζ_2	0.1	ρ	0.00625
σ_1	0.025	ε	0.000625

It can be understood that i_{L0} and i_L current variation ratios and C, C_0, and C_1 voltage variation ratios are low. V_0, which is the output voltage, is an actual DC voltage with slight fluctuation. In addition, I_0, which is the output current, is an actual DC waveform with slight fluctuation. The circuit controlling model of POSLLC is shown in Figure 7.

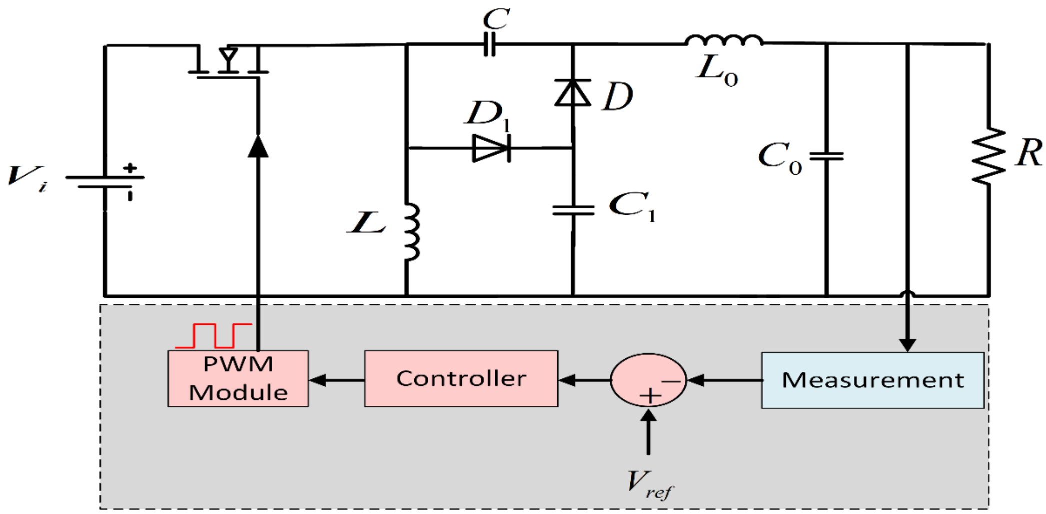

Figure 7. POSLLC circuit controlling model

The performances of controllers for tracking reference voltage are shown in Figure 8.

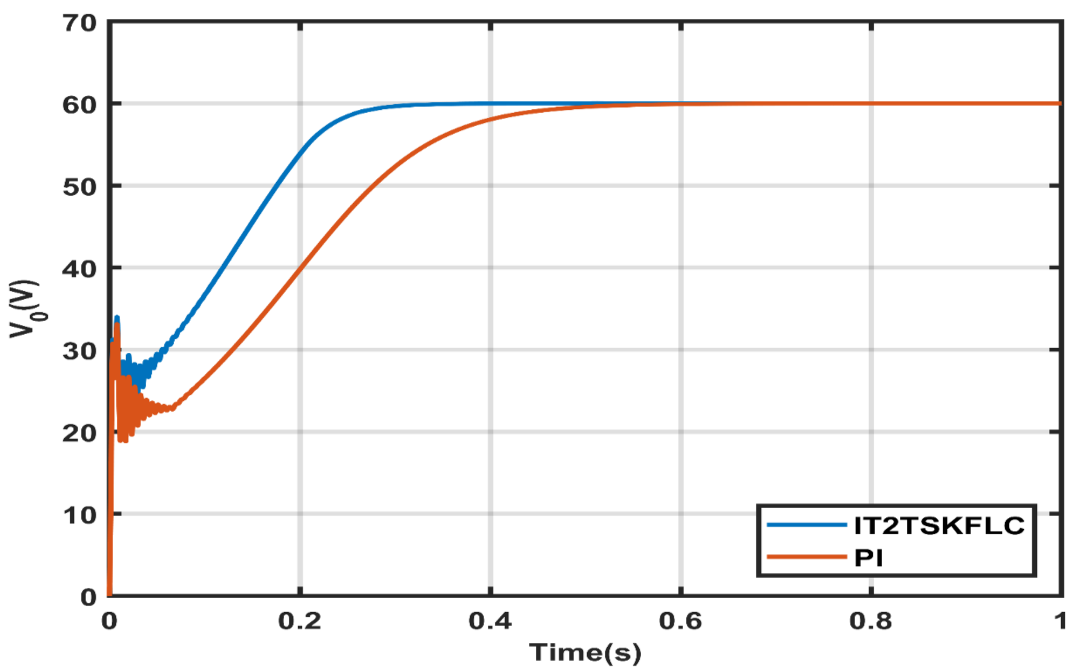

Figure 8. Dynamic responses of controllers

As shown in Fig. 8, the response of the proposed IT2TSKFLC converter is remarkably faster compared to PI converter, and reached reference voltage in a shorter period of time. The control signals of both controllers are shown in Figure 9.

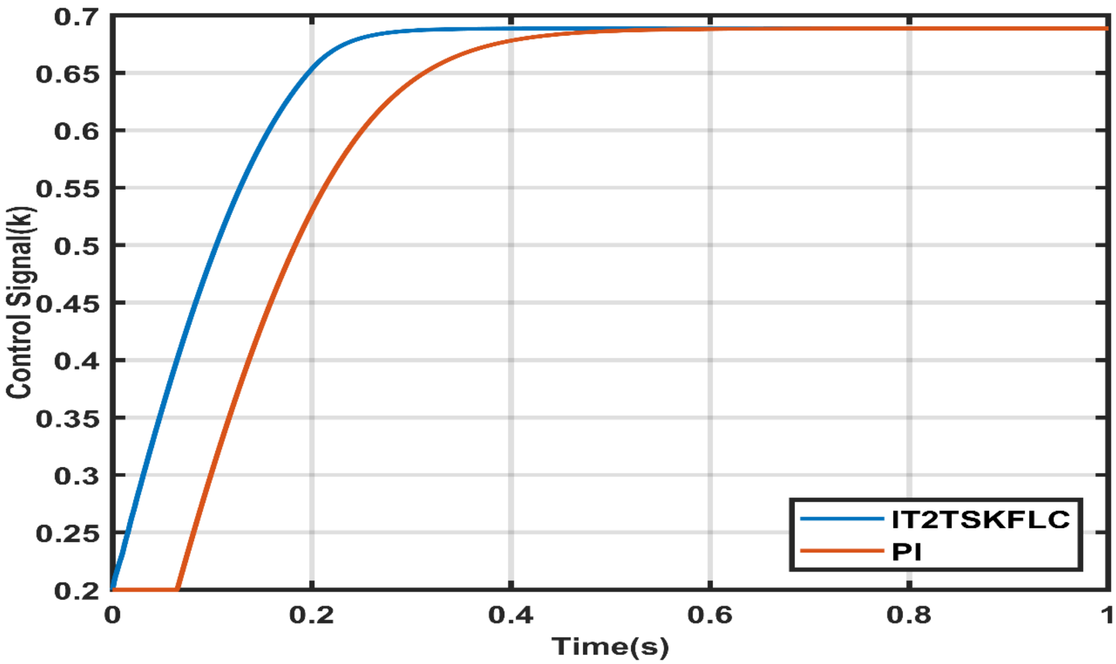

Figure 9. The control signals of both controllers

Conclusion and Discussion

The present study designed a simulation model using Matlab/Simulink environment in order to analyze the performances of the proposed IT2TSKFLC and PI converters for POSLLC circuit model. The findings of the simulation studies are showed that IT2TSKFLC has more efficient dynamic performance compared to PI controller.

The proposed intelligent controller based on IT2TSKFLC has a very durable dynamic performance compared to the classical PIcontroller. In future studies, it is aimed to contribute to the literature by using other intelligent control methods.

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Conflict of Interest: The authors declare that they have no conflict of interest.

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