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DYNAMIC PERFORMANCE COMPARISON 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 in order 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 Control, Luo Converter.*

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1. 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 structure for a high controlling performance against system uncertainties and parameter changes (Kumbasar *et al*., 2012). 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.

2. POSITIVE OUTPUT SELF LİFT LUO CONVERTER

Various circuit topologies using voltage lift technique can be found in the literature such as elementary circuit, self-lift circuit, re-lift circuit, triple-lift and quardruple-lift circuit. 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 shown in Fig. 1.

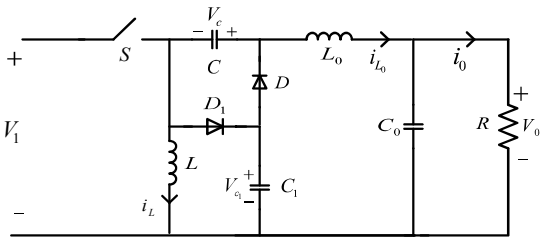


Fig. 1. POSLLC circuit model

When S switch is turned on, D_1 is on whereas D diode is off. At a steady state, inductor voltages are zero for a certain period of time. During switch on 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 off period. The equivalent circuit during switch on period is shown in Fig. 2.

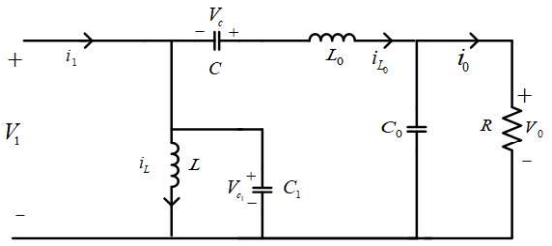


Fig. 2 POSLLC equivalent circuit during switch on period

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

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

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 turned off, D is on whereas D_1 diode is off. The equivalent circuit during switch off period is shown in Fig. 3.

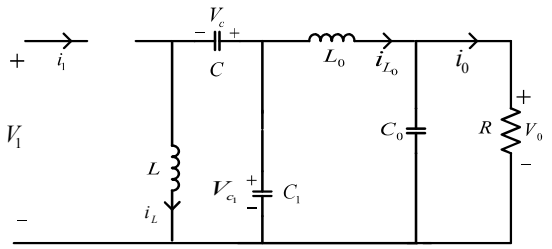


Fig. 3 POSLLC equivalent circuit during switch off period

During switch off 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.

$$I_0 = I_L \tag{2}$$

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

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. IT2TSKFLC consists of four main parts: fuzzifier, a rule base, a fuzzy inference, and a type reducer. 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-reduced set. The type reduced set is used for defuzzification process (Acikgoz, 2018). The internal structure of in IT2TSKFLC is shown in Fig. 4.

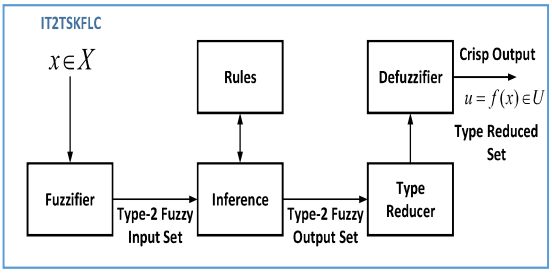


Fig. 4 The internal structure of IT2TSKFLC

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

$$R_i : IF\ x_1 \text{ is } \tilde{A}_{1i} \text{ AND } \ldots x_n \text{ is } \tilde{A}_{ni} \text{ THEN } y_i^* = c_{0i} + c_{1i}x_1 + \ldots + c_{ni}x_n \quad (4)$$

where i = 1…r represents the IF-THEN rules of the fuzzy system; $x_1, \ldots, x_n$ are input variables and $\tilde{A}_{ni}$ is membership function (MF) of IT2TSKFLC for the variable n and rule r; and y_i^* is the rule output; and $c_0 + c_1 + \ldots + c_n$ are the consequent parameters. In the present study; Gaussian type MF is preferred as shown in Fig.5. The mathematical equations of Gaussian type MF are expressed in Eqs. 5-6:

$$\bar{\mu}_{ij} = \exp\left\{-\frac{1}{2}\left(\frac{x_i - c_{ij}}{\bar{\sigma}_{ij}}\right)^2\right\} \quad (5)$$

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

Where, c_{ij} is the mean value, σ_{ij} is standard deviation, and x_i is the input variable.

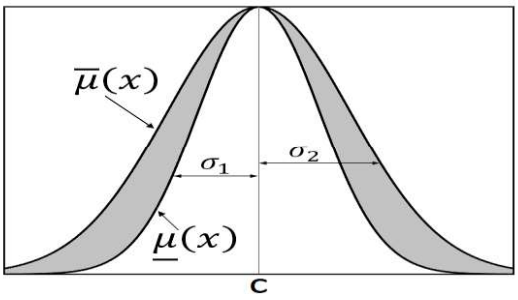


Fig.5. Gaussian type-2 fuzzy set

The t-norm operation is defined in Eq. 7:

$$f_i = \prod_{j=1}^{n} \mu(x_j) \quad (7)$$

A normalized firing strength can be defined in Eq.8:

$$\bar{f}_i = \frac{f_i}{\sum_{k=1}^{r} f_k} \quad (8)$$

$\bar{f}_i$ denotes the normalized firing strength. IT2TSKFLC includes lower and upper membership functions in case of uncertainties (Chang *et al*., 2011). The firing strengths of a fuzzy rule is defined as lower and upper using the t-norm operator in Eqs. 9-10, respectively.

$$\underline{f}_i = \prod_{j=1}^{n} \underline{\mu}(x_j) \quad (9)$$

$$\bar{f}_i = \prod_{j=1}^{n} \bar{\mu}(x_j) \quad (10)$$

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

$$Y_{BMM} = q\frac{\sum_{i=1}^{r} f_i\, y_i}{\sum_{i=1}^{r} f_i} + p\frac{\sum_{i=1}^{r} \bar{f}_i\, y_i}{\sum_{i=1}^{r} \bar{f}_i} \quad (11)$$

4. 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.

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt \quad (12)$$

In the present study, Ziegler–Nichols method is selected to adjust the parameters of the PI controller because it does not need a mathematical model of the system. The parameters Kp and Ki are designed from plant step response. From Ziegler–Nichols method, the parameters Kp and Ki of the controller are obtained as 0.001 and 5 for the POSLLC converter, respectively.

5. 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 Fig. 6.

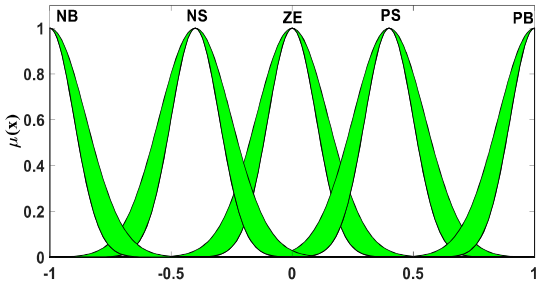


Fig. 6. Gaussian membership functions selected for the error and change of error

A value range of [-1, 1] was set for Gaussian membership functions. Linguistic variables used for the error and change of error in Matlab/Simulink simulation of the designed system 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

e \ de	NB	NS	ZE	PS	PB
NB	**NB**	**NB**	**NB**	**NS**	**ZE**
NS	**NB**	**NB**	**NS**	**ZE**	**PS**
ZE	**NB**	**NS**	**ZE**	**PS**	**PB**
PS	**NS**	**ZE**	**PS**	**PB**	**PB**
PB	**ZE**	**PS**	**PB**	**PB**	**PB**

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.

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

$$\zeta_2 = \frac{kR}{2MfL_0} \tag{14}$$

$$\rho = \frac{k}{2fCR} \tag{15}$$

$$\sigma_1 = \frac{M}{2fC_1R} \tag{16}$$

$$\varepsilon = \frac{k}{8Mf^2L_0C_0} \tag{17}$$

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

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

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_0	8 uF
R	100 Ω	C	10.67 uF
k	0.6667	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_0	1300 uF
R	100 Ω	C	1300 uF
k	0.6667	C_1	1300 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 ripple. In addition, I_0, which is the output current, is an actual DC waveform with slight ripple. The circuit controlling model of POSLLC is shown in Fig. 7.

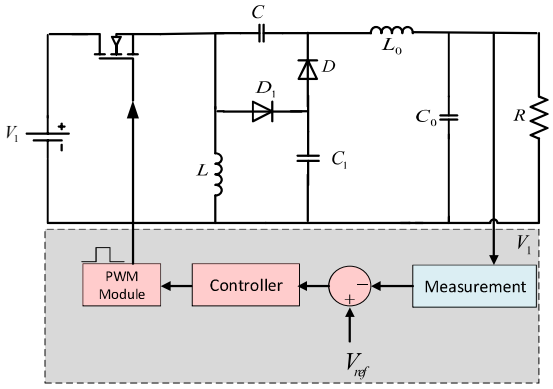


Fig. 7. POSLLC circuit controlling model

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

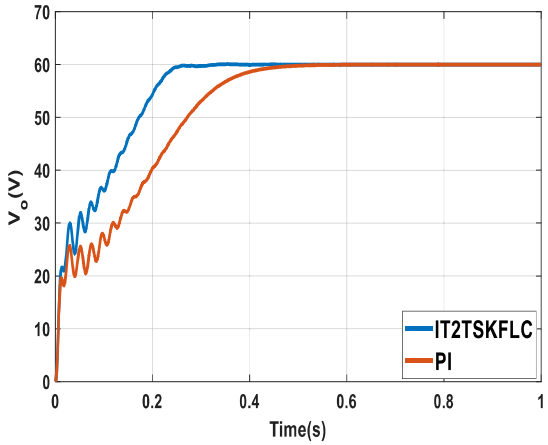


Fig. 8. Dynamic responses of controllers

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.

5. CONCLUSION

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 in terms of parameters such as rise time, settling time and steady state error.

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