

Enhanced Control of Polymer Electrolyte Membrane Fuel Cell Fed Basic Series Positive Super Voltage Lift Luo Converter Using Interval Type-2 Fuzzy Logic

Ahmet GANI^{1*} , İlknur UÇAR¹ 

¹Kayseri University, Faculty of Engineering, Architecture and Design, Department of Electrical and Electronics Engineering, Kayseri, Turkey

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Anahtar Kelimeler

Temel Seri Pozitif Süper
Gerilim Yükseltmeli
Dönüştürücü
PEM Yakıt Hücresi
Aralıklı Tip-2 Bulanık
Mantık

Graphical/Tabular Abstract (Grafik Özet)

The polymer electrolyte membrane fuel cell (PEM) fed basic series positive super voltage lift luo converter reached optimum current and voltage values under nominal and different operating conditions using an interval type-2 takagi-sugeno-kang (TSK) fuzzy controller in this study. / Bu çalışmada polimer elektrolit membran (PEM) yakıt pilinden beslenen temel seri pozitif süper gerilim yükseltmeli luo dönüştürücü aralıklı tip-2 takagi-sugeno-kang (TSK) bulanık denetleyici kullanılarak nominal ve farklı çalışma koşulları altında optimum akım ve gerilim değerlerine ulaşılmıştır.

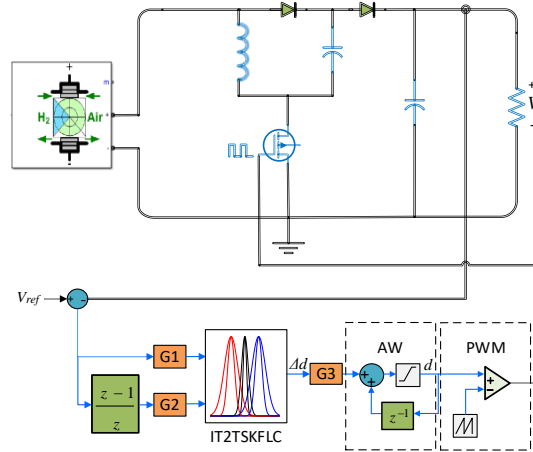


Figure A: The interval type-2 TSK fuzzy controller and PEM fuel cell fed basic series positive super voltage lift luo converter /**Şekil A:** PEM yakıt hücresi beslemeli temel seri pozitif süper gerilim yükseltmeli luo dönüştürücü ve aralıklı tip-2 TSK bulanık denetleyici

Highlights (Önemli noktalar)

- Efficient power transfer to the load. / Yüke verimli güç aktarımı
- Durable performance under nominal and different operating structures. / Nominal ve farklı çalışma koşulları altında dayanıklı performans
- Improvement average settling time of control system by 22.335% compared to the type-1 TSK fuzzy controller. / Tip-1 TSK bulanık denetleyiciye göre denetim sisteminin ortalama yerleşme süresinin %22.335 iyileştirilmesi

Aim (Amaç): The present study aims to control output voltage of PEM fed basic series positive super voltage lift luo converter via interval type-2 TSK fuzzy logic. /Bu çalışma PEM beslemeli temel seri pozitif süper gerilim yükseltmeli luo dönüştürücünün aralıklı tip-2 TSK bulanık mantık ile çıkış gerilimini denetlemeyi amaçlamaktadır.

Originality (Özgünlük): The control of the output voltage of the PEM fed basic series positive super voltage lift luo converter has been performed for the first time via interval type-2 TSK fuzzy logic. / PEM beslemeli temel seri pozitif süper gerilim yükseltmeli luo dönüştürücünün çıkış geriliminin denetimi aralıklı tip-2 TSK bulanık mantık ile ilk defa gerçekleştirilmiştir.

Results (Bulgular): Interval type-2 TSK fuzzy controller improved average settling time of system 22.335% compared to the type-1 TSK fuzzy controller. / Aralıklı tip-2 TSK bulanık denetleyici sistemin ortalama yerleşme süresini tip-1 TSK bulanık denetleyiciye göre 22,335% iyileştirmiştir.

Conclusion (Sonuç): The interval type-2 fuzzy controller provided a stable performance. / Aralıklı tip-2 TSK bulanık denetleyici kararlı bir çalışma sağlamıştır.



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Abstract

An eco-friendly and renewable energy source, Polymer Electrolyte Membrane (PEM) fuel cells offer various advantages such as stability and efficiency. The present study aims to control output voltage of PEM fed basic series positive super voltage lift luo (PSVLL) converter. The model, which consists of a fuel cell and a basic series PSVLL converter, was designed in Matlab/Simulink simulation environment. The control of the PSVLL converter output voltage was performed using an interval type-2 takagi-sugeno-kang fuzzy logic (IT2TSKFL) and type-1 takagi-sugeno-kang fuzzy logic (T1TSKFL) controllers comparatively. The simulation study results demonstrated that the PEM fuel cell fed basic series PSVLL converter reached optimal current and voltage values with IT2TSKFL under nominal and different operating conditions. Moreover, IT2TSKFL improved average settling time of control system by 22.335% compared to T1TSKFL controller.

Polimer Elektrolit Membran Yakıt Pili Beslemeli Temel Seri Pozitif Süper Gerilim Yükseltmeli Luo Dönüştürücünün Aralıklı Tip-2 Bulanık Mantık Kullanılarak Denetimi

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Öz

Çevre dostu ve yenilenebilir bir enerji kaynağı olan Polimer Elektrolit Membran (PEM) yakıt hücreleri kararlılık ve verimlilik gibi çeşitli avantajlar sunmaktadır. Bu çalışma, PEM yakıt pili beslemeli temel seri pozitif süper gerilim yükseltmeli luo (PVLL) dönüştürücünün çıkış gerilimini denetlemeyi amaçlamaktadır. Bir yakıt hücresi ve bir temel seri PSVLL dönüştürücüden oluşan model Matlab/Simulink benzetim ortamında tasarlanmıştır. PSVLL dönüştürücünün çıkış geriliminin denetimi karşılaştırmalı olarak aralıklı tip-2 takagi-sugeno-kang bulanık mantık (IT2TSKFL) ve tip-1 bulanık mantık (T1FL) denetleyiciler kullanılarak gerçekleştirilmiştir. Benzetim çalışması sonuçları PEM yakıt hücresinden beslenen temel seri PSVLL dönüştürücünün nominal ve farklı çalışma koşulları altında IT2TSKFL ile optimum akım ve gerilim değerlerine ulaşmıştır. Ayrıca IT2TSKFL denetim sisteminin ortalama yerleşme süresini T1TSKFL denetleyiciye kıyasla % 22.335 oranında iyileştirmiştir.

1. INTRODUCTION (GİRİŞ)

Polymer electrolyte membrane (PEM) fuel cell has benefits such as low operating temperature, high power density, low weight and eco-friendly nature [1-3]. Due to these benefits, PEM fuel cells are considered as one of the promising clean energy conversion systems of the future [4-5]. In today's world, the number of studies on power electronics

circuit structures are increasing day by day for highly efficient renewable energy sources. As fuel and photovoltaic cells are among renewable energy sources with a low output voltage, it is vital to increase output voltage via series and parallel circuits. However, this is likely to increase structure size and cost when greater energy is required. In this sense, many different power electronics have been

developed such as direct current-direct current (DC-DC) and isolated/non-isolated converters (Flyback, Cuk, Sepic, Zeta, Buck, Boost, Buck and Boost, and Luo) to manage the output voltage of cell fuels, photovoltaic panels and other renewable energy sources in various high energy applications [6-8]. Among the power electronics converter structures mentioned above, Luo converter is designed using on super voltage lift method. When compared with other power electronics converter circuit topologies, a basic series PSVLL converter yields a high voltage gain at a lower duty ratio [9]. Thus, it seems feasible to benefit from PSVLL power electronics converter in a system with an output voltage such as fuel cell. DC-DC power electronics circuits possess a non-linear structure [10]. Because conventional control methods (proportional+integral; proportional+derivative;proportional+integral+derivative) are designed for nominal operating conditions (NOCs), they cannot achieve an effective control performance under different operating conditions. Conventional controllers fail in the control of non-linear systems [11]. In recent years, many different intelligent controller structures have been developed in parallel with innovations in the field of controller systems. One of these controller systems is fuzzy logic controller (FLC). As these controllers are designed independently of the mathematical model of the controlled system, they are widely used. Conventional type-1 FLCs have been widely used in different systems for many years, yielding quite satisfying results. However, it was also reported that they could not succeed in the control of the systems with a certain level of uncertainty. Therefore, type-2 FLC was proposed by L. Zadeh as an advanced and improved version of conventional type-1 FLCs [12]. While uncertainty regions are used in membership functions for the system control of type-2 FLCs, certain membership values are used in type-1 FLCs. As a result, type-2 FLCs are acknowledged as a more successful controller system in terms of overcoming uncertainties [13-14]. In the existing literature, there are several studies on the control of PEM fuel cell fed DC power electronics converter circuit structures. S. Kart [6] performed the control of the output voltage of a PEM fuel cell fed cascade boost converter using a proportional+integral (PI) and Lyapunov based (PI) controller to compare the performances of two controllers. There was a 26.4% decrease in the rise time of the output voltage of the entire system using the new Lyapunov-based controller compared to the conventional PI controller. There were also a decrease rate of 91.6%

and 79.9% in settling time and overshoot, respectively. A. Karaarslan et al. [15] designed a PEM fuel cell fed buck converter and controlled its output voltage using PI and one-cycle controller. The output voltages were tested based on the input voltage; reference voltage and R_{load} changes. The output voltage response of the PI controller was faster compared to one-cycle controller, indicating that both control systems were suitable for buck converter. Ö. Özkara et al. [16] studied the control of the output voltage of a PEM fuel cell fed isolated fly-back converter using PI and one-cycle controllers. PI controller provided a higher rising time and a less percent overshoot compared to one-cycle controller. A. Bilhan [17] designed a super-lift DC/DC converter and conventional boost DC/DC converter circuit structures for fuel cell applications. The simulation results demonstrated that the output voltage waveforms of converters were investigated for the same duty ratio, and higher voltage levels were obtained via the super-lift DC/DC converter compared to conventional boost DC/DC converter. Unlike previous studies, the present study designs a basic series PSVLL converter for PEM fuel cell applications and proposes an IT2TSKFL controller to control the output voltage of the designed converter. The main innovations can be summarized as follows:

The IT2TSKFL controller structure efficiently (with a lower current and voltage ripple and a higher power density) converts the power of the PEM fuel cell to the load resistance.

The IT2TSKFL controller structure displays a stabilized performance under nominal and different operating structures.

Other parts of the study are organized as follows:Section 2 describes the material and method, while Section 3 discusses the findings. Section 4 presents the conclusion.

2. MATERIALS AND METHODS (MATERİYAL VE METOD)

2.1. Basic Series PSVLL Converter (Temel seri PSVLL dönüştürücü)

The present study uses a basic series PSVLL converter, which contains a semi-conductor switching element S , an inductor L ; two capacitors C_1 and C_2 and two diodes, as shown in Figure 1.

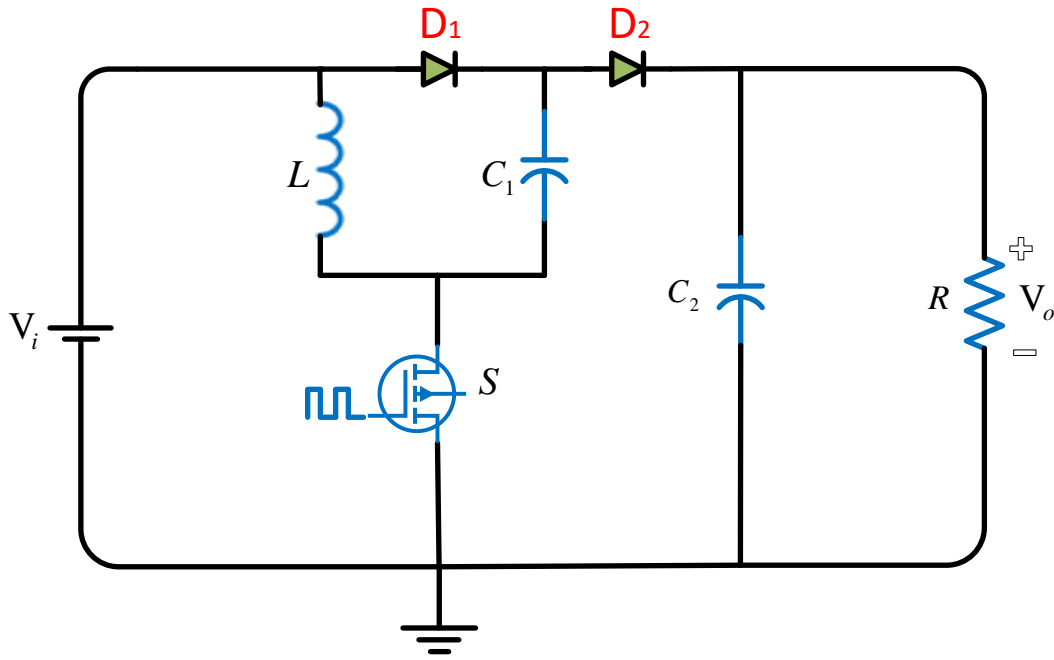


Figure 1. Basic series PSVLL converter (Temel seri PSVLL dönüştürücü)

\$S\$ semi-conductor switching element and \$D_1\$ diode transmission forms the circuit shown in Figure 2. In this case, the current flows through \$L\$ inductor, and \$C_1\$ capacitor is loaded with \$V_i\$ voltage. When \$S\$ semi-conductor switching element and \$D_1\$ diode is cut off, the circuit in Figure 3 is obtained, which decreases the inductor voltage to \$(2V_i-V_o)\$ value [18]. The voltage gain (\$G\$) of the basic series PSVLL converter can be defined as follows:

$$G = \frac{V_o}{V_i} = \frac{2-d}{1-d} \quad (1)$$

For the analysis of basic series PSVLL converter, based on the change in current ratio (\$\delta\$) on \$L\$ inductor and the change in voltage ratios on \$C_1\$ and \$C_2\$ capacitors (\$\epsilon\$), the boundary values of the circuit elements are calculated using Equation (2-3).

$$\delta = \frac{d(1-d)^2 R}{2(2-d)fL} \quad (2)$$

$$\epsilon = \frac{d}{2RfC_{1,2}} \quad (3)$$

The change in current ratio (\$\delta\$) and change in voltage ratios on \$C_1\$ and \$C_2\$ capacitors (\$\epsilon\$) were selected as 0.2 and 0.01 respectively. Actual converter element values need to be higher than the calculated boundary element values for an effective continuous operation mode (CCM) [19-20]. The element values for the PSVLL converter are presented in Table 1.

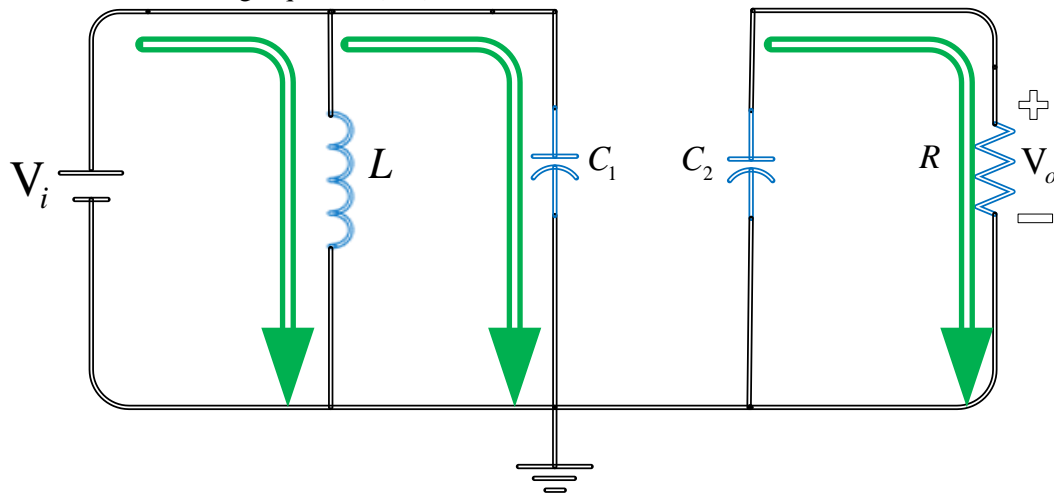


Figure 2. \$S\$ semi-conductor switching element and \$D_1\$ diode transmission (S yarı iletken anahtarlama elemanı ve \$D_1\$ diyot iletimde)

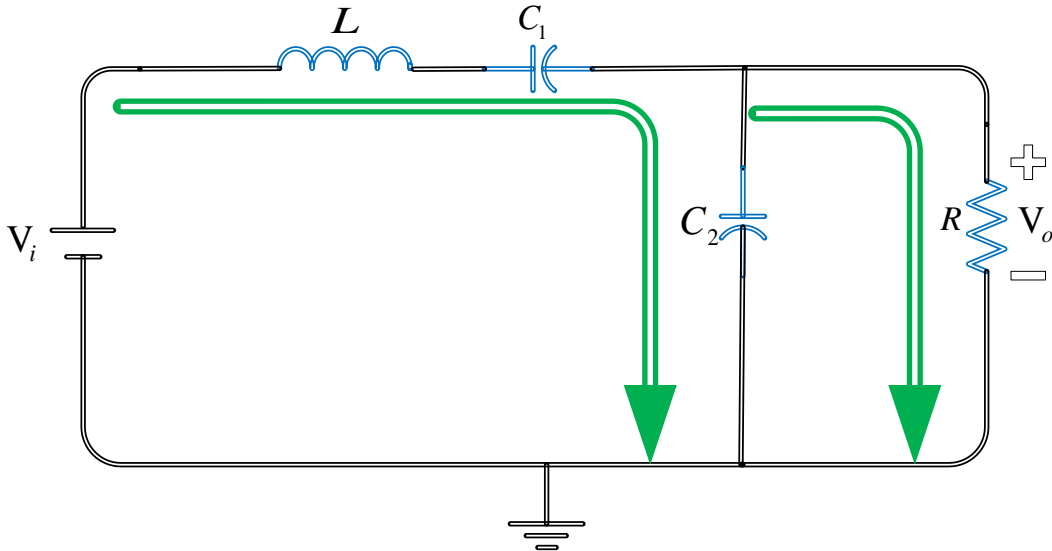


Figure 3. S semi-conductor switching element and D_1 diode cutoff (S yarı iletken anahtarlama elemanı ve D_1 diyot kesimde)

Table 1. The specified, calculated boundary and selected values of the PSVLL converter (PSVLL dönüştürücüsünün belirlenen, hesaplanan ve seçilen değerleri)

Specified Values		
Input Voltage	V_{in}	45V
Output (Load) Voltage	V_o	180V
Load Resistance	R	5Ω
Switching Frequency	f	50Khz
The variation ratio of the current flow on the L inductor	δ	0.2
The variation ratio of the voltage on $C_{1,2}$ capacitors	ϵ	0.01
Calculated Boundary Values		
Inductor	L_K	0.13mH
Capacitor	$C_{1,2K}$	$6.66\mu\text{F}$
Selected Values		
Inductor	L	1mH
Capacitor	$C_{1,2}$	$22\mu\text{F}$

2.2 PEM Fuel Cell (PEM Yakıt Hücresi)

The changes in voltage and current in a PEM fuel cell is non-linear [21]. Current-voltage (I-

V) and current-power (I-kW) characteristics of a PEM fuel cell operating at a nominal power of 6 kW are shown in Figure 4.

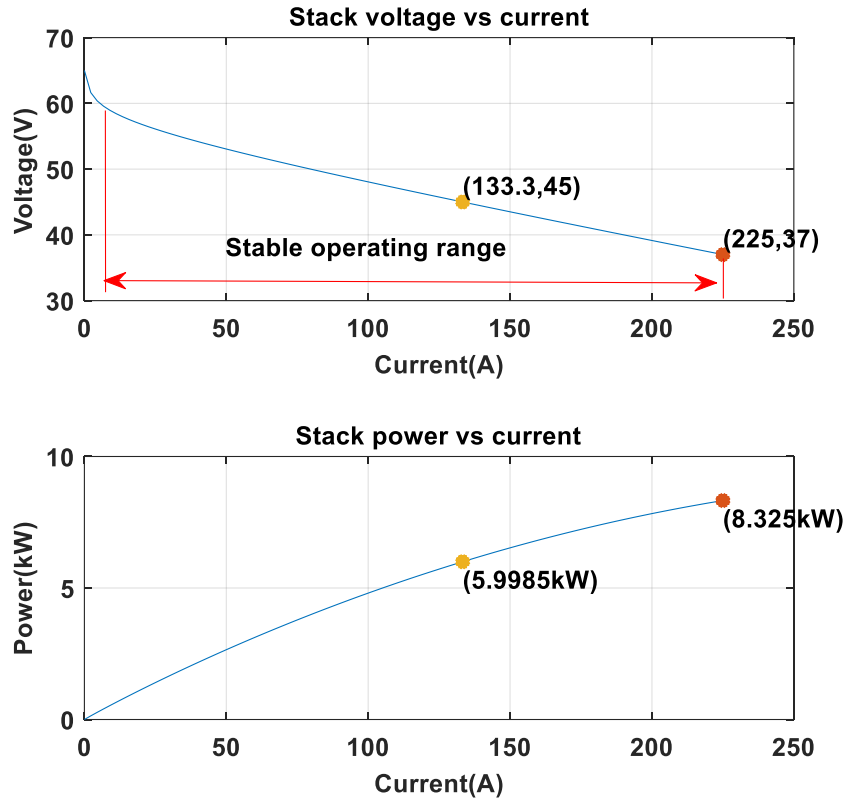


Figure 4. (I-V) and (I-kW) characteristics of a PEM fuel cell operating at a nominal power of 6 kW (6 kW nominal güçte çalışan bir PEM yakıt pilinin (I-V) ve (I-kW) karakteristikleri)

As shown in I-V characteristic in Figure 4, the current from the fuel cell is inversely proportional to the cell voltage. On the other hand, in I-V characteristic, the current from the fuel cell is directly proportional to the power from it until it reaches the maximum power level (8.325kW).

2.3 IT2FL Controller Structure (IT2FL denetleyici yapısı)

One of the non-linear DC-DC converter circuit topologies, PEM fuel cell fed basic series PSVLL converter must be controlled with a high performance in order to prevent the impact of changes in its output voltage. Therefore, it requires a suitable non-linear controller structure [22]. Type-2 FLCs are widely preferred because they display a more effective controlling performance against

system uncertainties compared to type-1 FLCs [23]. Type-2 FLCs also offer a different version with a lower computational load called interval type-2 fuzzy logic (IT2FL) controllers [24]. As shown in Figure 5 clearly, it consists of a fuzzifier, a rule base, an inference mechanism, a type reducer and defuzzification, and it was used in the present study. The inputs of IT2FL controller are error $e(n)$ and change in error $\Delta e(n)$. These inputs are scaled using G1 and G2 gains, and transferred to the fuzzifier. G3 is the input gain of the controller system.

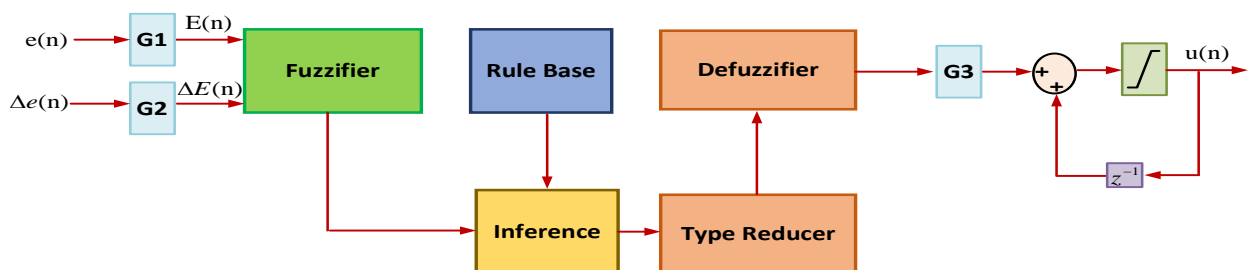


Figure 5. IT2FL controller structure (IT2FL denetleyici yapısı)

$$E(n) = e(n)G1 \tag{4}$$

$$\Delta E(n) = [\Delta e(n)]G2 \tag{5}$$

The fuzzified inputs help us procedure type-2 fuzzy outputs after the inference mechanism employs the rule base. In the present study, three Gaussian membership functions (MFs) were used for each input, as expressed in the following equation.

$$\mu_{\tilde{A}}(x) = e^{\left\{-\frac{1}{2}\left(\frac{x-m}{\sigma}\right)^2\right\}} \tag{6}$$

Here, x is the input variable. m and σ are the center of Gaussian MF and standard deviation, respectively. Type-2 Gaussian MF is shown in Figure 6. Three lower and upper Gaussian MFs for error (e) and change in error (Δe) in the present study are shown in Figure 7.

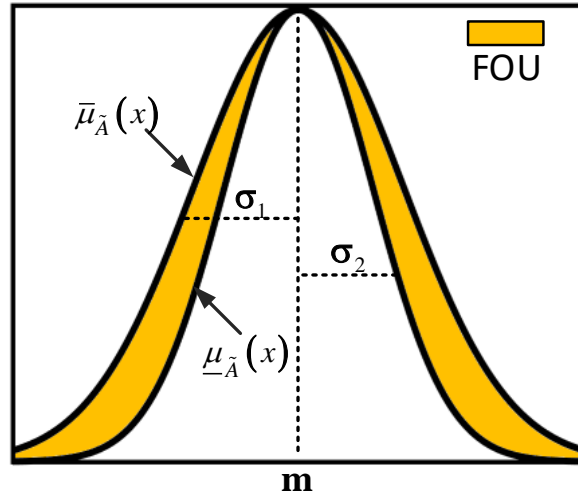


Figure 6. Gaussian MF [21] (Gauss MF)

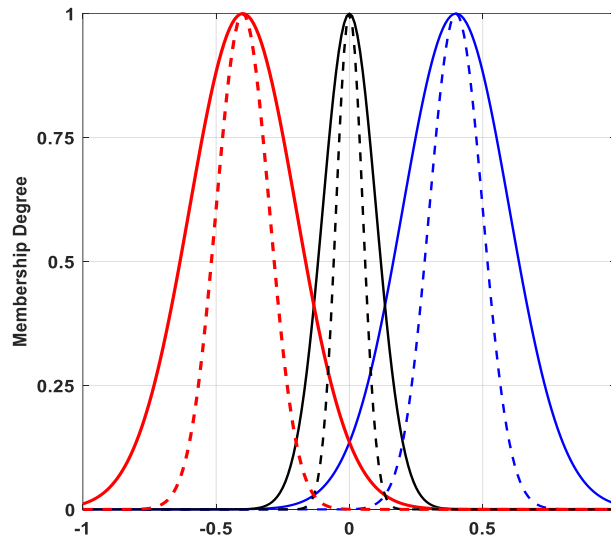


Figure 7. Lower and upper Gaussian MFs for (e) and (Δe) (e and Δe için alt ve üst Gauss üyelik fonksiyonları)

Lower and upper Gaussian MFs in Figure 7 were selected between $[-1,+1]$. The region between lower and upper MFs represents the footprint of uncertainty (FOU) [25]. When takagi-sugeno-kang (TSK) method represented by a linear function is used in the final parameters of this controller, it is called an interval type-2 TSK fuzzy logic controller

(IT2TSKFLC), and its rule base is defined as follows:

$$R^i: \text{If } E(n)\tilde{A}_1^i \text{ and } \Delta E(n)\tilde{A}_2^i, \text{ Then } u_n = a_1^i E(n) + a_2^i \Delta E(n) \tag{7}$$

Here, i ($i=1,\dots,25$) denotes the number of rules. a_1^i and a_2^i are the final parameters. The firing strengths

of lower and upper MFs for the i^{th} rule can be expressed as follows:

$$\underline{f}^i = \underline{\mu}_{\tilde{A}_1^i}(E(n)) * \underline{\mu}_{\tilde{A}_2^i}(\Delta E(n)) \quad (8)$$

$$\underline{f}^i = \underline{\mu}_{\tilde{A}_1^i}(E(n)) * \underline{\mu}_{\tilde{A}_2^i}(\Delta E(n)) \quad (9)$$

Here * t-norm is the operator. $\underline{\mu}_{\tilde{A}_j^i}$ and $\underline{\mu}_{\tilde{A}_j^i}$ represents lower and upper MF of the i^{th} rule. Normalization is performed using the following equations.

$$\underline{F}^i = \frac{\underline{f}^i}{\sum \underline{f}^i} \quad (10)$$

$$\underline{F}^i = \frac{f^i}{\sum f^i} \quad (11)$$

Biglarbegan-Melek-Mendel (BMM) [26] method was used for the type reducer and defuzzification, as it requires a lower computational load.

$$U_L(n) = \frac{\sum_i^M \underline{F}^i U_i(n)}{\sum_i^M \underline{F}^i} \quad (12)$$

$$U_R(n) = \frac{\sum_i^M \underline{F}^i U_i(n)}{\sum_i^M \underline{F}^i} \quad (13)$$

$$U(n) = qU_L(n) + (1 - q)U_R(n) \quad (14)$$

Here, q is a parameter which can be adjusted by the user. It was set to 0.5 in the present study.

3. FINDINGS AND DISCUSSION (BULGULAR VE TARTIŞMA)

It is of vital importance to select switching frequency, circuit element and input and output voltage values beforehand in order to design a basic series PSVLL converter.

3.1. Simulation Studies (Benzetim çalışmaları)

Input-output (load) voltage, load value and switching frequency values of the basic series PSVLL converter used the simulation studies are given in Table 1. The IT2TSKFL controller structure and block diagram of the PEM fuel cell fed basic series PSVLL converter are shown in Figure 8.

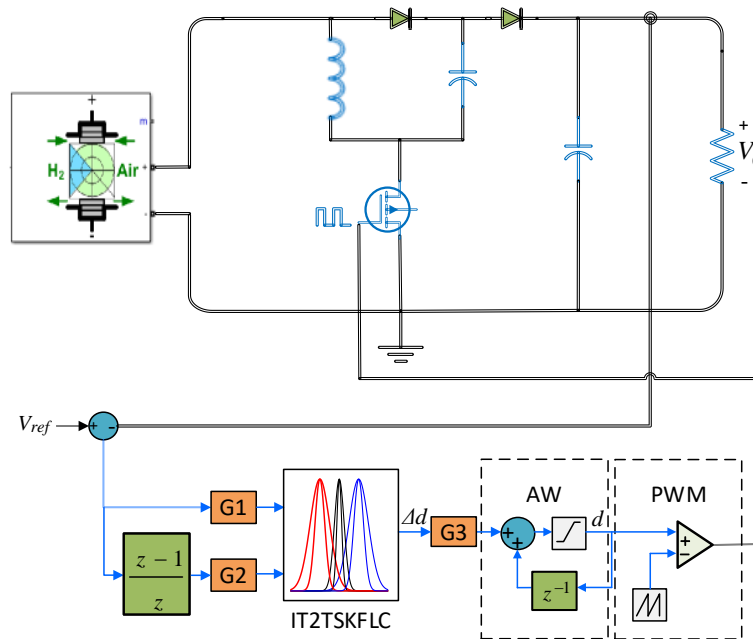


Figure 8. The IT2TSKFL controller structure and block diagram of the PEM fuel cell fed basic series PSVLL converter (PEM yakıt hücresi beslemeli temel seri PSVLL dönüştürücünün blok şeması ve IT2TSKFL denetleyici yapısı)

As shown in Figure 8, V_{ref} is the intended output reference voltage (V_0) of the basic series PSVLL converter. V_0 is the output voltage of the basic series PSVLL converter. After error and change in error values between the reference and output voltage are found, they are applied to the IT2TSKFL controller using $G1$ and $G2$ gain constants. Δd in the output of the IT2TSKFL

controller is the change in controller signal, and it is applied to the input of AW block using $G3$ gain constant. Finally, d control signal in the output of AW block is applied to the semi-conductor switching element using pulse width modulation (PWM) block. Matlab/Simulink environment was employed to assess the performance of the IT2TSKFL controller. The first step in the

simulation studies was to analyze the suitability of the PEM fuel cell fed basic series PSVLL converter to the design criteria in Table 1 under NOCs. To this aim, the PEM fuel cell fed basic series PSVLL converter was operated at the constant (0.667) duty ratio in MATLAB/Simulink environment. Total

simulation time elapsed was 1s, and the sampling time was taken as $0.1\mu s$. The output voltage of the PEM fuel cell fed basic series PSVLL converter for the constant duty ratio under NOCs is shown in Figure 9.

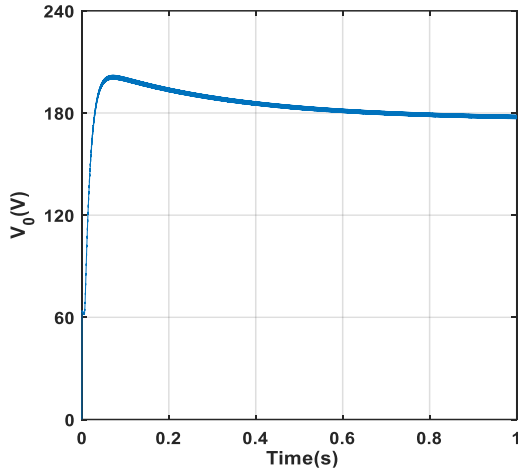


Figure 9. The output voltage of the PEM fuel cell fed basic series PSVLL converter for the constant duty ratio under NOCs. (NOC altında sabit görev oranı için PEM yakıt hücresinden beslenen temel seri PSVLL dönüştürücünün çıkış gerilimi)

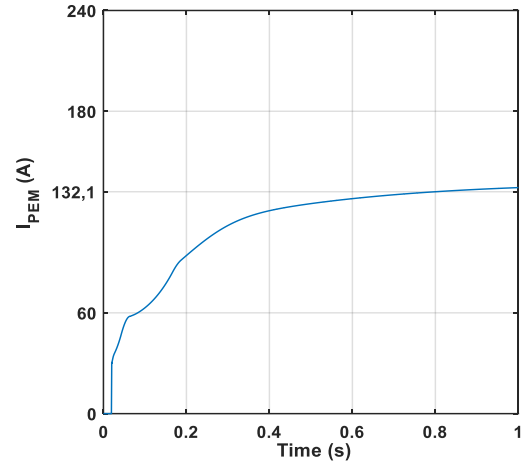


Figure 10. The current obtained from the PEM fuel cell fed basic series PSVLL converter under NOCs with the IT2TSKFL controller (IT2TSKFL denetleyici ile NOC altında PEM yakıt hücresinden beslenen temel seri PSVLL dönüştürücünden elde edilen akım)

It can be seen in Figure 9 that the output voltage reached 180V at the specified boundary variation ratio at 0.8s, which justified the accuracy of the parameters selected for the converter design. Secondly, the current (I_{PEM}), power (P_{PEM}), and cell voltage (V_{PEM}) values from the PEM fuel cell under

NOCs via the IT2TSKFL controller were analyzed and shown in Figure 10, 11 and 12, respectively. As shown in Figure 10, the current obtained from the PEM fuel cell under NOCs via the IT2TSKFL controller is 132.1 A.

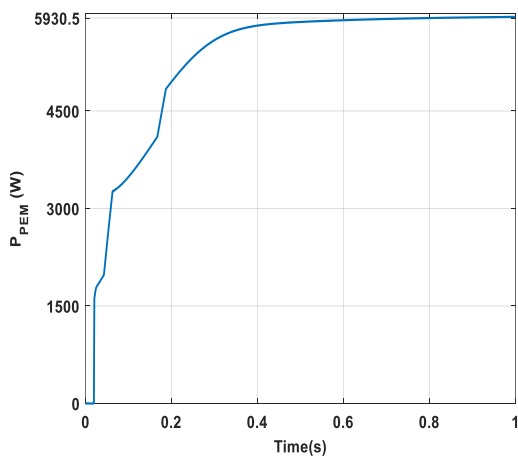


Figure 11. The power obtained from the PEM fuel cell fed basic series PSVLL converter under NOCs with the IT2TSKFL controller (IT2TSKFL denetleyici ile NOC altında PEM yakıt hücresinden beslenen temel seri PSVLL dönüştürücünden elde edilen güç)

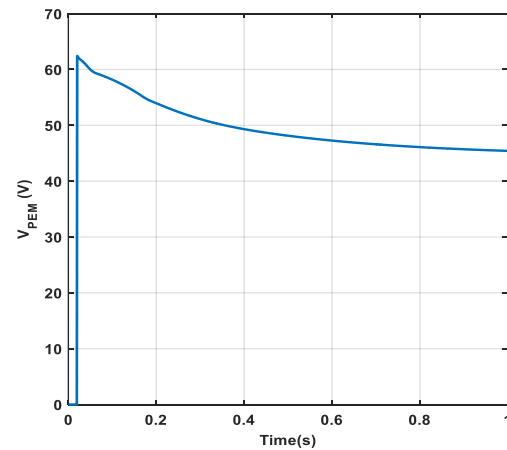


Figure 12. The voltage obtained from the PEM fuel cell fed basic series PSVLL converter under NOCs with the IT2TSKFL controller (IT2TSKFL denetleyici ile NOC altında PEM yakıt hücresinden beslenen temel seri PSVLL dönüştürücünden elde edilen gerilim)

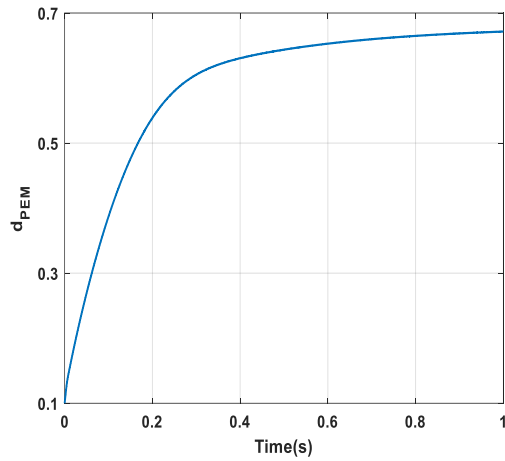


Figure 13. The control signal of the IT2TSKFL controller (d_{PEM}) (IT2TSKFL denetleyicinin denetim sinyali (d_{PEM}))

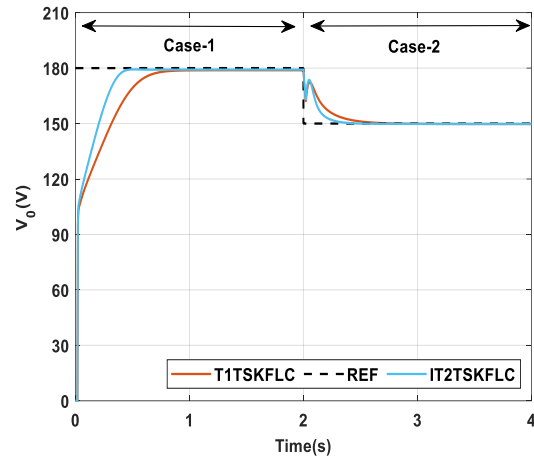


Figure 14. The dynamic response of the IT2TSKFL controller and T1TSKFLC against reference voltage changes (IT2TSKFL denetleyicinin ve T1TSKFLC'nin referans gerilim değişikliklerine karşı dinamik tepkisi)

In the last step of the simulation studies, the dynamic performance of the IT2TSKFL controller and T1TSKFLC were analyzed for different step reference voltage values in MATLAB/Simulink environment in terms of settling time. In this respect, reference voltage (V_0) value was decreased from 180V to 150V. Total simulation time elapsed

was 4s, while the sampling time was taken as $0.1\mu s$. Simulation results for different step reference voltage values obtained from IT2TSKFL controller and T1TSKFLC are shown in Fig. 14. The settling time values of IT2TSKFL controller and T1TSKFLC are given in Table 2 for two different cases.

Table 2. The settling time values of IT2TSKFL controller and T1TSKFLC (IT2TSKFL denetleyici ve T1TSKFLC'nin yerleşme süresi değerleri)

Cases Controllers	IT2TSKFL	T1TSKFLC
Case 1	1s	1.35s
Case 2	0.65s	0.8s

As can be seen in Table 2, compared to T1TSKFLC, IT2TSKFL controller could offer a lower settling time, improving settling times of PEM fuel cell fed

basic series PSVLL converter by 25.92% and 18.75% under different reference voltage changes for two different cases, respectively.

4. CONCLUSIONS (SONUÇLAR)

In the present study, a PEM fuel cell fed basic series PSVLL converter was designed. The most important advantage of the designed controller is its capacity to yield a high output voltage with a low duty ratio. In addition, the output (load) voltage was controlled using IT2TSKFL controller to create a more stabilized system at different operating points. The results of the simulation studies indicated that

the designed converter structure operated with optimal efficiency at the specified boundary current and voltage ripple ratios and that the IT2TSKFL controller ensured a stabilized operation. In future studies, the operation of the PEM fuel cell at the maximum power point will be discussed.

DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The authors of this article declare that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

Ahmet GANI: He conducted the literature review, research, editing and consultancy.

Literatür taraması, araştırma, düzenleme ve danışmanlık yapmıştır.

İlknur UÇAR: She conducted simulation studies and writing process.

Benzetim çalışmaları ve yazım sürecini yürütmüştür.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

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