

## Interval type-2 fuzzy logic controller based DPC-SVM algorithm for PWM rectifier

**Abstract.** In this paper, we propose an interval type-2 fuzzy logic controller (IT-2 FLC) for Direct Power Control (DPC) of three phases Pulse Width modulation (PWM) rectifier based on virtual flux estimation. The precise mathematical model of the system is not required to design the proposed controller. The design procedure of this controller is explored in detail in this paper. To study the operation and the controllability of the proposed IT-2-FLC in the DPC-SVM algorithm under different conditions, the PWM rectifier with the whole control scheme has been simulated using MATLAB SIMULINK program. The results of simulation show the excellent performances of the proposed system.

**Streszczenie.** W tym artykule proponujemy interwałowy kontroler logiki rozmytej typu 2 (IT-2 FLC) do bezpośredniego sterowania mocą (DPC) trójfazowego prostownika z modulacją szerokości impulsu (PWM) na podstawie estymacji strumienia wirtualnego. Procedura projektowania tego regulatora została szczegółowo omówiona w tym artykule. Aby zbadać działanie i sterowność proponowanego IT-2-FLC w algorytmie DPC-SVM w różnych warunkach, przeprowadzono symulację prostownika PWM z całym schematem sterowania za pomocą programu MATLAB SIMULINK. Wyniki symulacji wskazują na doskonałe osiągnięcia proponowanego systemu. (Sterownik z logiką rozmytą typu 2 interwałowy oparty na algorytmie DPC-SVM dla prostownika PWM)

**Keywords:** Interval type-2 fuzzy logic controller, virtual flux estimator, PWM rectifier, compensation of voltage and load fluctuation.

**Słowa kluczowe:** .kontroler z logiką rozmytą, prostownik PWM, sterownik interwałowy

### Introduction

The three-phase pulse width-modulated (PWM) rectifier is a more interesting solution in renewable energy applications; it's used for the grid connection of wind turbines. That is thanks to viable advantages such as [1-14]:

- Bidirectional power flow;
- Low harmonic distortion of line current;
- Regulation of input power factor to unity;
- Adjustment and stabilization of dc-link voltage;
- Reduced DC filter (capacitor size).

The development of the PWM rectifiers control methods is possible due to the progress in the processors, they allow an establishment of sophisticated algorithms that are fast and performed.

This article proposes the mixed DPC-SVM approach of PWM rectifier; it is an adaptation of VFOC (Virtual Flux Oriented Control) and VF-DPC (Virtual Flux oriented Direct Power Control) techniques. This method gives more efficient control of this converter, by controlling directly the active and reactive power.

In order to achieve a unity power-factor a control of the power reactive to zero is carried out. The reference of the active power is obtained by DC voltage control block. Generally, PI controller [15-18] is used to control the DC bus voltage. The PI controller based approach requires precise linear mathematical model which is difficult to obtain. Also, it fails to perform satisfactorily under parameter variations, non-linearity, and load disturbances [7-11]. Recently, fuzzy logic controller has generated a great deal of interest in various applications and has been introduced in the power electronics field [17-22]

The advantages of fuzzy logic controllers over the conventional PI controller are that they do not need an accurate mathematical model; they can work with imprecise inputs, can handle nonlinearity, and may be more robust than the conventional PI controller.

This paper presents an analysis by simulation of a Direct Power Control (DPC) of three phases PWM rectifier. To optimize this control, an interval type-2 fuzzy logic controller is developed to adjust the energy storage of the DC voltage to its reference and the active & reactive power. The reference power computation is based on virtual flux estimation. A SVM algorithm is used to generate switching signals of the rectifier.

### Direct power control of PWM rectifier

Generally, the control techniques which are commonly used could be classified as direct or indirect control strategies. The indirect control is characterized by a modulator (Pulse Wide Modulation PWM or other) that computes the turn-on/turn-off times of the converter's switches along a switching period through the evaluation of the voltage reference. This voltage reference is issued by the controller, which idealizes the converter as a dependent continuous voltage source. On the other hand, direct control techniques establish a direct relation between the behavior of the controlled variable and the state of the converter's switches.

The figure 1 shows the whole configuration of the direct instantaneous active and reactive power control for a PWM rectifier. The network is represented as a balanced voltage source.

The direct power control (DPC-SVM) is based on the instantaneous active & reactive power control loops and SVPWM modulator block.

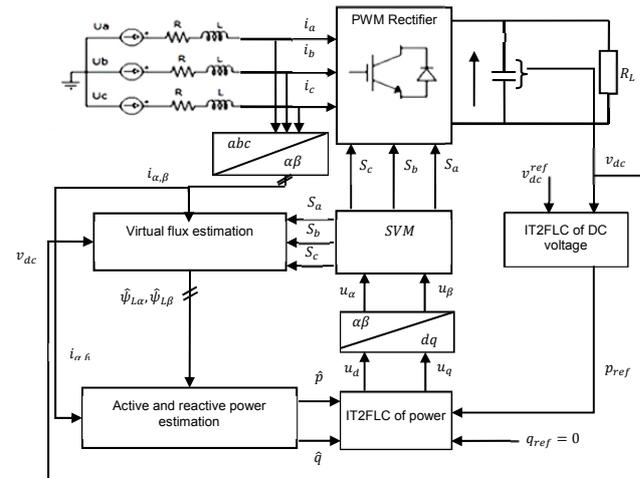


Fig.1. Configuration of DPC-SVM for PWM rectifier.

## Virtual Flux Estimation

The virtual flux approach can be used to improve the VOC (Voltage Oriented Control) and DPC methods. In virtual flux estimation method, the imposed line voltage in combination with AC side inductors is assumed as a virtual AC motor [18].

Based on the measured DC-link voltage  $U_{dc}$  and the converter switch states  $S_a, S_b, S_c$  the rectifier input voltages are estimated as follows:

$$(1) \quad u_{s\alpha} = \sqrt{\frac{2}{3}} U_{dc} \left( S_a - \frac{1}{2}(S_b + S_c) \right)$$

$$(2) \quad u_{s\beta} = \frac{1}{\sqrt{2}} U_{dc} (S_b - S_c)$$

Then, the virtual flux  $\Psi_L$  components are calculated in stationary ( $\alpha$ - $\beta$ ) coordinates system by:

$$(3) \quad \Psi_{L\alpha(est)} = \int \left( u_{s\alpha} + L \frac{di_{L\alpha}}{dt} \right) dt$$

$$(4) \quad \Psi_{L\beta(est)} = \int \left( u_{s\beta} + L \frac{di_{L\beta}}{dt} \right) dt$$

The virtual flux components calculation is shown in Fig. 2.

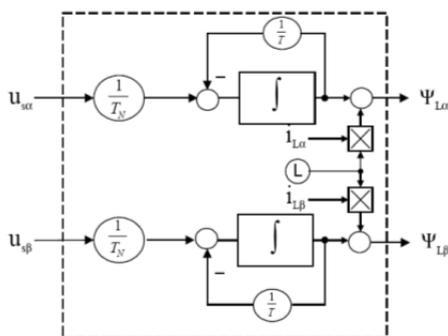


Fig.2. Block scheme of virtual flux estimator

## Instantaneous power estimation based on the virtual flux

The voltage equation can be written as:

$$(5) \quad \bar{u}_L = R\bar{i}_L + \frac{d}{dt}(L\bar{i}_L + \bar{\Psi}_s)$$

In practice,  $R$  can be neglected, giving:

$$(6) \quad \bar{u}_L = L \frac{d\bar{i}_L}{dt} + \frac{d\bar{\Psi}_s}{dt} = L \frac{d\bar{i}_L}{dt} + \bar{u}_s$$

Using complex notation, the instantaneous power can be calculated as follows:

$$(7) \quad p = \text{Re}(\bar{u}_L \cdot \bar{i}_L^*)$$

$$(8) \quad q = \text{Im}(\bar{u}_L \cdot \bar{i}_L^*)$$

where  $*$  denotes the conjugate line current vector. The line voltage can be expressed by the virtual flux as:

$$(9) \quad \bar{u}_L = \frac{d}{dt} \bar{\Psi}_L = \frac{d}{dt} (\Psi_L e^{j\omega t}) = \frac{d\Psi_L}{dt} e^{j\omega t} + j\omega \Psi_L e^{j\omega t} = \frac{d\Psi_L}{dt} e^{j\omega t} + j\omega \bar{\Psi}_L$$

Where  $\bar{\Psi}_L$  denotes the space vector and  $\Psi_L$  its amplitude. For the virtual flux oriented  $d$ - $q$  coordinates,  $\Psi_L = \Psi_{Ld}$ , and the instantaneous active power can be calculated from (7) and (9) as

$$(10) \quad p = \frac{d\Psi_{Ld}}{dt} i_{Ld} + \omega \Psi_{Ld} i_{Lq}$$

For sinusoidal and balanced line voltages, equation (10) is reduced to

$$(11) \quad \frac{d\Psi_{Ld}}{dt} = 0$$

$$(12) \quad p = \omega \Psi_{Ld} i_{Lq}$$

Which means that only the current components orthogonal to the flux  $\Psi_L$  vector, produce the instantaneous active power. Similarly, the instantaneous reactive power can be calculated as:

$$(13) \quad q = -\frac{d\Psi_{Ld}}{dt} i_{Lq} + \omega \Psi_{Ld} i_{Ld}$$

and with (11) it is reduced to:

$$(14) \quad q = \omega \Psi_{Ld} i_{Ld}$$

However, to avoid coordinate transformation into  $d$ - $q$  coordinates, the power estimator for the DPC system should use stator-oriented quantities, in  $\alpha$ - $\beta$  coordinates (Fig.1).

Using (7) and (8)

$$(15) \quad \bar{u}_L = \frac{d\Psi_L}{dt} \Big|_{\alpha} + j \frac{d\Psi_L}{dt} \Big|_{\beta} + j\omega(\Psi_{L\alpha} + j\Psi_{L\beta})$$

$$(16) \quad \bar{u}_L \bar{i}_L^* = \left\{ \frac{d\Psi_L}{dt} \Big|_{\alpha} + j \frac{d\Psi_L}{dt} \Big|_{\beta} + j\omega(\Psi_{L\alpha} + j\Psi_{L\beta}) \right\} (i_{L\alpha} - j i_{L\beta})$$

That gives

$$(17) \quad p = \left\{ \frac{d\Psi_L}{dt} \Big|_{\alpha} i_{L\alpha} + \frac{d\Psi_L}{dt} \Big|_{\beta} i_{L\beta} + \omega(\Psi_{L\alpha} i_{L\beta} - \Psi_{L\beta} i_{L\alpha}) \right\}$$

$$(18) \quad q = \left\{ \frac{d\Psi_L}{dt} \Big|_{\alpha} i_{L\alpha} + \frac{d\Psi_L}{dt} \Big|_{\beta} i_{L\beta} + \omega(\Psi_{L\alpha} i_{L\alpha} + \Psi_{L\beta} i_{L\beta}) \right\}$$

For sinusoidal and balanced line voltage the derivatives of the flux amplitudes are zero. The instantaneous active and reactive powers can be computed as [15-18]

$$(19) \quad p = \omega(\Psi_{L\alpha} i_{L\beta} - \Psi_{L\beta} i_{L\alpha})$$

$$(20) \quad q = \omega(\Psi_{L\alpha} i_{L\alpha} - \Psi_{L\beta} i_{L\beta})$$

The measured line currents  $i_a, i_b$  and the estimated virtual flux components  $\hat{\Psi}_{L\alpha}, \hat{\Psi}_{L\beta}$  are delivered to the instantaneous power estimator block (PE) as depicted in figure 3.

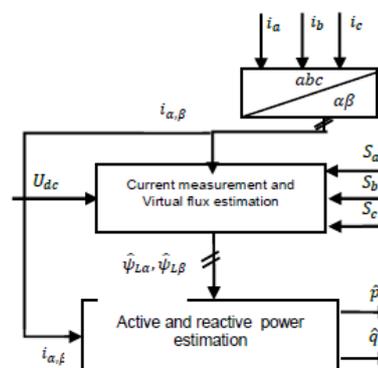


Fig.3. Instantaneous power estimator based on virtual flux

### Type-2 Fuzzy logic control

Type-2 fuzzy sets (T2 FSs) were first proposed by Zadeh in 1975 as an extension to type-1 (T1) FSs. It has been gaining considerable attentions recently. The IT2 FSs has been used in many applications [12-15], and they often demonstrate better performance than their T1 counterparts.

Figure 4 shows the schematic diagram of an IT2 FLS. It is similar to its T1 counterpart, the major difference being that at least one of the FSs in the rule-base is an IT2 FS.

Hence, the outputs of the inference engine are IT2 FSs, and a type-reducer is needed to convert them into a T1 FS before defuzzification can be carried out. Type reduction (TR) is usually performed by the iterative Karnik-Mendel (KM) algorithms [23], which are computationally intensive. The extra computational cost of IT2 FLSs over T1FLSs may hinder them from certain cost-sensitive real-world applications, because an IT2 FLS requires a more powerful processor, which increases the cost of the overall system.

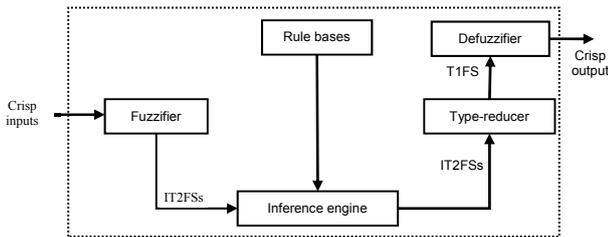


Fig.4. Diagram of an IT2 FLS.

There have been many different approaches for reducing the computational cost of IT2 FLSs, including both hardware implementation optimization and software algorithmic optimization.

### Synthesis of the IT2 FLC

The type-2 FLS has the same schema as type-1 FLS with difference in output processing as you can see on figure 5.

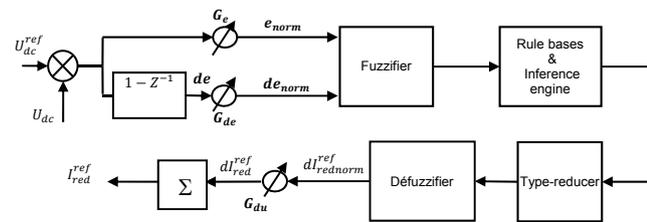


Fig.5. Structure of IT-2 FLC

Rules of type-2 FLS contain type-2 fuzzy sets (at least one)

$$(21) \quad R^i: \text{IF } e \text{ is } \tilde{F}_e^i \text{ AND } de \text{ is } \tilde{F}_{de}^i \text{ THEN } dI_{red}^{ref} \text{ is } \tilde{G}^i;$$

Where:

$M$  is the number of rules,

$\tilde{F}_e^i, \tilde{F}_{de}^i$  and  $\tilde{G}^i$  are type-2 fuzzy membership functions.

Type reduction reduces the type-2 fuzzy sets into type-1 fuzzy sets and can be made by iterative algorithm developed by Karnik and Mendel [23].

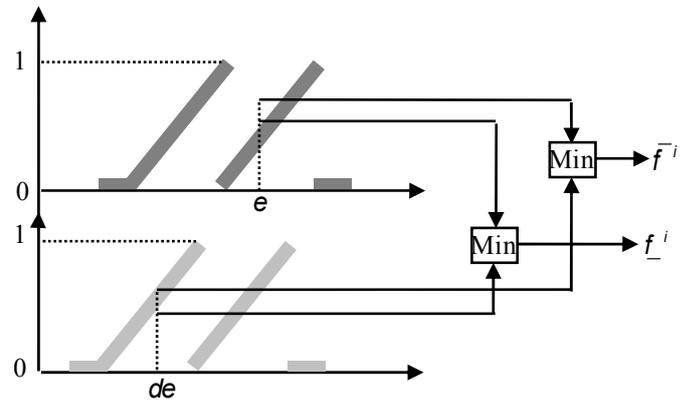
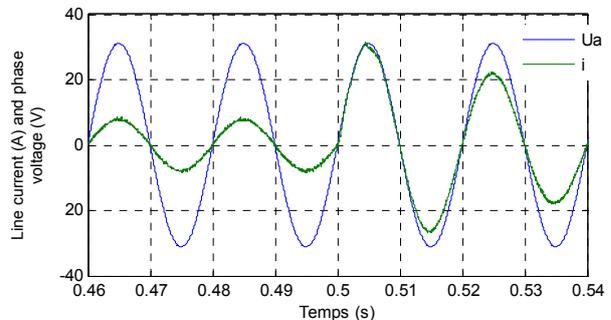
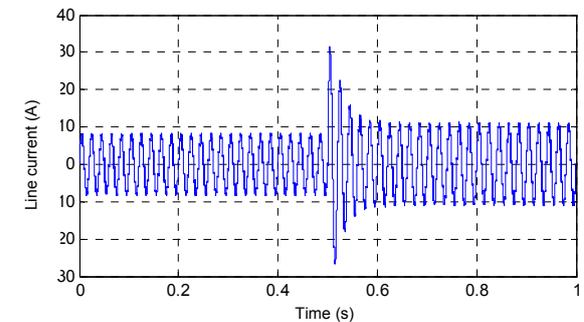
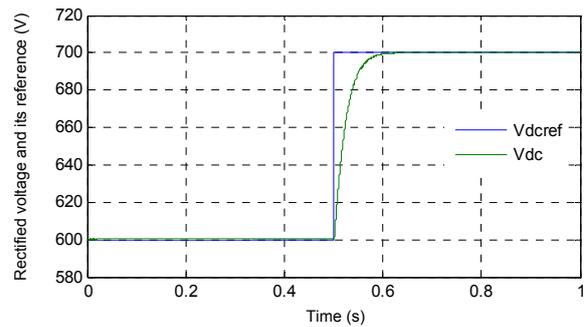


Fig.6. Fuzzification with T-norm minimum

### Results and discussion

These results are obtained for purely sinusoidal supply line voltage.

Figure 7 shows the behaviour of this method for a step reference voltage, the dc-bus voltage follows its reference which varies from 600V to 700V. The increment of the dc-bus voltage leads to the increment of the active power and the line current after a small transition, however the reactive power, the line voltage and estimated line voltage remain unchanged.



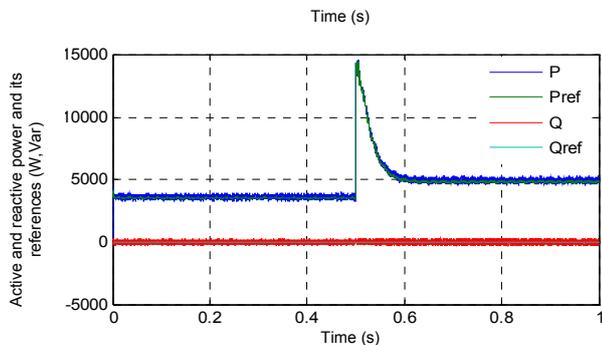


Fig.7. Performances of the PWM rectifier controlled by DPC under voltage variation condition

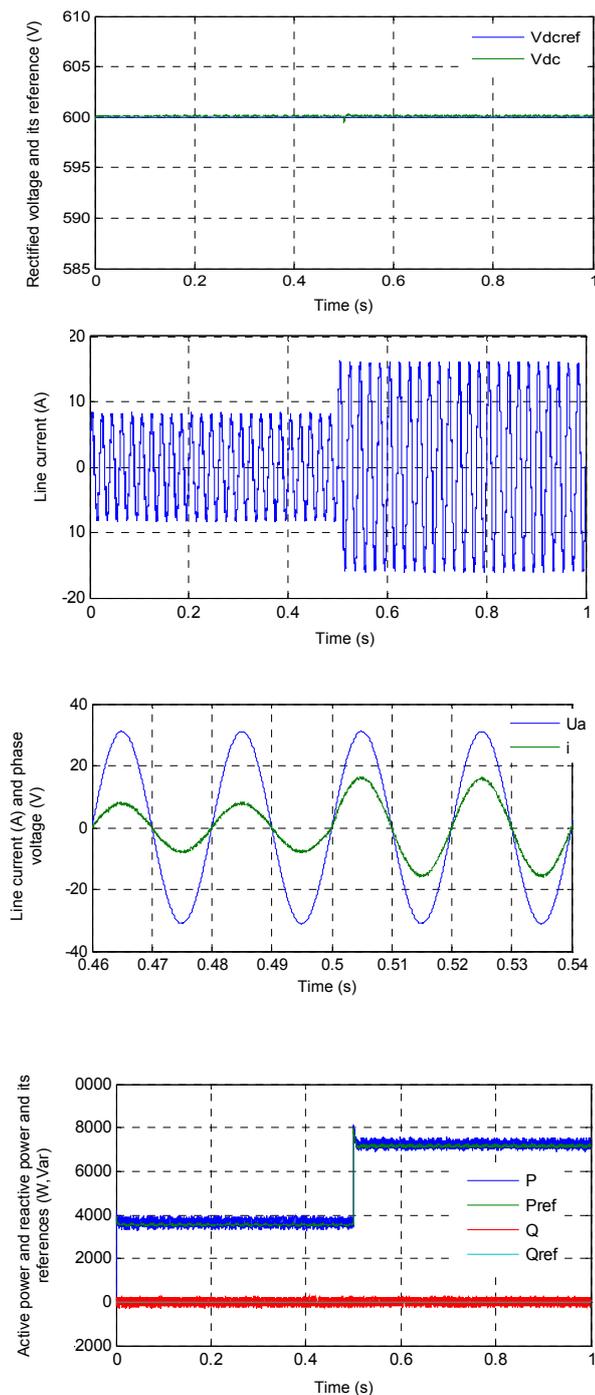


Fig.8. Test of robustness under load fluctuation

Figure 8 shows waveforms with resistive load variation, (decrement by half at 0.5s). We note that the current increases with the decrement of the load, the active power always follows the current value, however the reactive power remain controlled in its reference (zero), which means the current and the voltage are in-phase. Finally, the estimation of the line voltage and the control of the dc-bus voltage remains insured.

The spectral analysis of the line current, shows that all the harmonics of weak rang are well attenuated which give a THD = 2.7 %.

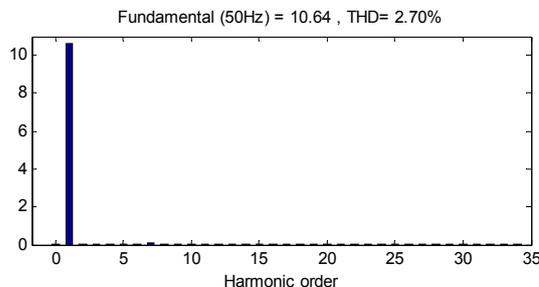


Fig.9. Spectral analysis of the line current

The different tests of simulation prove the reliability and the good control dynamic performances of the proposed IT2FLC.

### Conclusion

This work was devoted to study an interval type-2 fuzzy logic controller (IT-2 FLC) for Direct Power Control (DPC) of three phases Pulse Width modulation (PWM) rectifier based on virtual flux estimation.

A dc-bus voltage control is carried out in order to have the reference active power. Whereas, the reference reactive power is set directly equal to zero for unity power factor.

The digital simulation has shown the dynamic performances of the DPC-SVM under a different test, dc-bus voltage reference variation and load variation.

The simulation results show that the proposed approach allows to have better results than with the classic DPC approach.

**Authors:** Dr. Reda KARA, Laboratory of Advanced Electronic Systems (LSEA), Department of Electrical Engineering, University Dr Yahia Farès, Médéa, Algeria, E-mail: [kara\\_reda@hotmail.com](mailto:kara_reda@hotmail.com); Pr. Abdelhalim TLEMCANI, Electrical Engineering and Automatic Research Laboratory, Department of Electrical Engineering, University Dr Yahia Farès, Médéa, Algeria, E-mail: [h\\_tlemcni@yahoo.fr](mailto:h_tlemcni@yahoo.fr); Nawel HASSAOUI, Phd student, Electrical Engineering and Automatic Research Laboratory, Department of Electrical Engineering, University Dr Yahia Farès, Médéa.

### REFERENCES

- [1] Xu Zhang, Guojun Tan, Zhan Liu, Qiang Wang, Weifeng Zhang and Tao Xia, "Finite Control Set Model Predictive Direct Power Control of Single-phase Three-level PWM Rectifier Based on Satisfactory Optimization", IEEE Access, pp. 220058 - 220068, January 2021.
- [2] Xiong Xiao, Yujuan Wu, Jiantao Su, Yongjun Zhang and Jingzhi Zhou, "An Improved Precise Power Control of Voltage Sensorless-MPC for PWM Rectifiers", IEEE Access, vol. 8, pp. 220058 - 220068, December 2020.
- [3] Hui Ma Yun Lu, Kaitong Zheng and Tianchuan Xu, "Research on the Simplified SVPWM for Three-Phase/ Switches Y-Type Two-Level Rectifier", IEEE Access, vol. 8, pp. 214310 - 214321, November 2020.
- [4] Navid H Golkhandan, Farzad Tahami and Majid Reza Salehi, "A Harmonic Elimination Method For Three-Phase PWM Rectifier To Reduce Computational Complexity", 28th Iranian Conference on Electrical Engineering (ICEE), 2020.

- [5] Seyed Majid Hashemzadeh, Rana Rostami, VafaMarzang and Seyed Hossein Hosseini, "Direct Power Control of PWM Three-Phase Rectifier Using the Predictive Method: Aims to Reduce THD", 28th Iranian Conference on Electrical Engineering (ICEE), 2020.
- [6] Hasan Komurcugil and Sertac Bayhan, "Sliding Mode Control Strategy for Three-Phase Three-Level T-Type PWM Rectifiers with Capacitor Voltage Imbalance Compensation", IECON 2019 - 45th Annual Conference of the IEEE Industrial Electronics Society, 2019.
- [7] Durga Nair S., GreeshmaNadh and Arun Rahul S., "A Novel Predictive Control for an Active Front End Rectifier using Lyapunov Stability Criteria", IECON 2019 - 45th Annual Conference of the IEEE Industrial Electronics Society, 2019.
- [8] June-Seok Lee ; Kyo-Beum Lee, "An Open-Switch Fault Detection Method and Tolerance Controls Based on SVM in a Grid-Connected T-Type Rectifier With Unity Power Factor", IEEE Transactions on Industrial Electronics, vol. 61, no. 12, pp. 7092 – 7104, 2014.
- [9] Gao Shi-hong ; Qian Xiao-long, "Research on modelling and control of three-level PWM rectifier system", The 26th Chinese Control and Decision Conference (2014 CCDC), pp. 3813 - 3817, 2014.
- [10] Zhang, Y.; Qu, C., "Direct Power Control of a Pulse Width Modulation Rectifier Using Space Vector Modulation Under Unbalanced Grid Voltage", IEEE Transactions on Power Electronics, vol. PP, no. 99, 2014.
- [11] June-Seok Lee ; Kyo-Beum Lee, "An Open-Switch Fault Detection Method and Tolerance Controls Based on SVM in a Grid-Connected T-Type Rectifier With Unity Power Factor", IEEE Transactions on Industrial Electronics, vol. 61, no. 12, pp. 7092 – 7104, 2014.
- [12] Dos Santos, E.C. ; Rocha, N. ; Jacobina, C.B., "Suitable Single-Phase to Three-Phase AC–DC–AC Power Conversion System", IEEE Transactions on Power Electronics, vol. 30, no. 2, pp. 860 - 870 2014.
- [13] Xin Zhou ; Hongjun Chen ; Hao Xu ; Lin Li, "Modeling and deterministic robust control of a three-phase four-switch PWM voltage-source rectifier based on direct power control", IEEE 4th Annual International Conference on Cyber Technology in Automation, Control, and Intelligent Systems (CYBER), pp. 94 - 99, 2014.
- [14] Alves de Melo Bento, A.; Perez Vieira, P.K. ; Cabral da Silva, E.R., "Application of the One-Cycle Control Technique to a Three-Phase Three-Level NPC Rectifier", IEEE Transactions on Industry Applications, vol. 50, no. 2, pp. 1177 - 1184, 2014.
- [15] T. Noguchi, H. Tomiki, S. Kondo, and I. Takahashi, "Direct power control of PWM converter without power-source voltage sensors," *IEEE Trans. Ind. Applicat.*, vol. 34, pp. 473–479, May/June 1998.
- [16] Gerardo Escobar, Aleksandar M. Stankovic, Juan M. Carrasco, E. Galván and Romeo Ortega, "Analysis and Design of Direct Power Control (DPC) for a Three Phase Synchronous Rectifier via Output Regulation Subspaces," *IEEE Trans. Power.Electronics.*, vol. 18, No. 3, May 2003.
- [17] Mariusz Malinowski, Marek Jasin'ski and Marian P. Kazmierkowski, "Simple Direct Power Control of Three-Phase PWM Rectifier Using Space-Vector Modulation (DPC-SVM)", *IEEE Trans. ind. Electronics*, vol. 51, No. 2, April 2004.
- [18] M. Malinowski, M. P. Kazmierkowski, S. Hansen, F. Blaabjerg, and G.D Marques, "Virtual flux based direct power control of three-phase PWM rectifiers." *IEEE Trans. Ind. Applicat.*, vol. 37, pp. 1019–1027, July/Aug. 2001.
- [19] Yildirim, M. T. A. Basturk and M. E. Yuksel, "A detail-preserving type-2 fuzzy logic filter for impulse noise removal from digital images," *Proc. IEEE FUZZ Conference*, pp. 751-756, London, UK, July 2007.
- [20] Wu, K. C., "Fuzzy Interval Control of Mobile Robots," *Computers Elect. Eng.*, vol. 22, pp. 211-229, 1996.
- [21] Wu, H. and J. M. Mendel, "Classification of battlefield ground vehicles using acoustic features and fuzzy logic rule-based classifiers," *IEEE Trans. on Fuzzy Systems*, vol. 15, pp. 56-72, February, 2007.
- [22] Torres, P. and D. Sáez, "Type-2 Fuzzy Logic Identification Applied to the Modeling of a Robot Hand," *Proc. IEEE FUZZ Conference*, Paper # FS0216, Hong Kong, China, June 2008.
- [23] Karnik, N. N. and J. M. Mendel, "Type-2 Fuzzy Logic Systems: Type-Reduction," in *Proc. IEEE Conference on Systems, Man and Cybernetics*, pp. 2046-2051, San Diego CA, Oct., 1998.