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A robust intelligent nonlinear control for a VSC-based HVDC station

***Abstract**. This paper investigates a robust intelligent non-linear controller for a high-voltage direct current transmission (HVDC) station based on a voltage source converter (VSC). The proposed controller combines fuzzy logic (FL) and sliding mode (SM) techniques. The sliding mode technique is used to model parameter uncertainties, and fuzzy logic is employed to handle non-linearity. The simulation results show that the proposed controller is more efficient under various unfavourable operation conditions compared to other techniques.*

***Streszczenie,** W artykule zbadano solidny inteligentny nieliniowy sterownik stacji wysokonapięciowej prądu stałego (HVDC) opartej na konwerterze źródła napięcia (VSC). Proponowany sterownik łączy techniki rozmyte (FL) i ślizgowe (SM). Do modelowania niepewności parametrów wykorzystywana jest technika trybu ślizgowego, a do obsługi nieliniowości wykorzystywana jest logika rozmyta. Wyniki symulacji pokazują, że proponowany sterownik jest bardziej wydajny w różnych niesprzyjających warunkach pracy w porównaniu z innymi technikami. (**Solidne inteligentne sterowanie nieliniowe dla stacji HVDC opartej na VSC**)*

Keywords: Voltage Source Converter, High Voltage Direct Current transmission system, Sliding Mode, Fuzzy Logic.
Słowa kluczowe: Konwerter źródła napięcia, System transmisji prądu stałego wysokiego napięcia, tryb przesuwny, logika rozmyta.

Introduction

In recent years, the need for electric power increases continually. The connection of the networks to other sources of energy can be a practical solution to answer this demand. Nevertheless, the interconnection in alternative voltage can't be constantly practicable, specifically to deal with problems of the liberalizing electrical network [1]. In order to transmit power to loads cost-effectively and reliably, The DC interconnection is particularly advantageous over long distances or for underwater connections [2].

The major requisite in a DC power transmission system is the accurate control of active and reactive power flow to maintain the system voltage steadiness. This is attained via an electronic converter and its capability to convert electrical energy from AC to DC or vice versa. There are essentially two structure types of three-phase converters possible for this conversion procedure, current source converters (CSC) and voltage source converters (VSC). The VSC-HVDC system has been an efficient solution to fix the flaw of traditional CSC-HVDC due to the self-turn-off feature of Insulated Gate Bipolar Transistor (IGBT) technology and Pulse Width Modulation (PWM). Furthermore, the VSC-HVDC system has clear advantages in the dispersed generation grid connection [3][4].

The mathematical model is used to create controllers for the VSC-HVDC system. On the other hand, extrinsic uncertainty interference, such as stochastic fluctuation of load problems in the AC system and DC link, can easily influence the real physical system. As a result, it's necessary to build VSC-HVDC controllers that increase transient stability while also minimizing the effects of uncertainties and external perturbations [5].

Many studies on VSC-HVDC control have been conducted. The vector control approach based on classical proportional-integral (PI) controllers has traditionally been considered [6]. However, this approach has some flaws, such as the stability issue caused by the effects of interaction between the inner and outer loops. Many other methods of control have been proposed in literature like robust control [7] [8][9], back-stepping [10], Finite-time stabilization [11], optimal control [5], and adaptive control techniques [12]. These techniques are used to create nonlinear controllers that are described by complex techniques and by a lack of complete knowledge of typical system dynamics.

Therefore, the sliding mode control (SMC) is one of the numerous useful control methodologies for a big type of uncertain system [13]. Sliding mode control has been adopted as an adequate control design for nonlinear systems; the important properties of SMC are fast response, robustness against uncertainties, insensitivity to bounded disturbances, good transient performance, and ease of calculation compared to traditional control systems [14][15][16].

In addition, fuzzy control has been used in the context of difficult ill-defined processes, particularly those which can be handled by a proficient human operator without the information of their underlying dynamics [17] [18]. Also, it can deal with extreme uncertainties.

In this context, a fuzzy sliding mode controller is proposed here for VSC-HVDC station systems; fuzzy logic is used to eliminate all the disadvantages of the classical controller and to improve its operability [19].

The present paper is organized as follows: a nonlinear mathematical model of the VSC-HVDC in the synchronous d-q reference frame is presented, the proposed FSM controller theory design is developed, and finally, the simulation results of the application of the proposed controller to control VSC-HVDC station system is given. It presents the effectiveness of the proposed controller compared to classical linear and nonlinear controllers.

VSC-based HVDC station Modelling

Fig (1) illustrates the VSC-HVDC substation model. The voltage source converter (VSC) is connected to the AC network via equivalent impedance (R_s +jL_s), and to a DC capacitor Con the DC side.

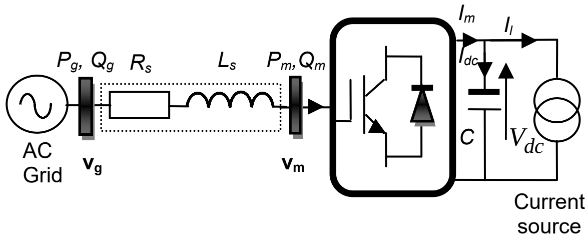

Fig.1. VSC-HVDC station model

To obtain the dynamic model of the VSC-HVDC system, Kirchhoff's second law is applied between VSC and PCC, and Kirchhoff's first law is applied on the DC -Link voltage side [20].
On the AC side, we obtain:

(1) $$L_s \frac{d\mathbf{i_s}}{dt} + R_s \mathbf{i_s} = \mathbf{v_g} - \mathbf{v_m}$$

where $\mathbf{i_s}, \mathbf{v_g}, \mathbf{v_m}$ are respectively the three-phase AC current and voltage of both sides of the phase reactance.

Equation (1) can be written after applying Park transformation:

(2) $$\begin{aligned} \frac{di_{sd}}{dt} &= -\frac{R_s}{L_s} i_{sd} + \omega i_{sq} - \frac{1}{L_s} v_{md} + \frac{1}{L_s} v_{gd} \\ \frac{di_{sq}}{dt} &= -\omega i_{sd} - \frac{R_s}{L_s} i_{sq} - \frac{1}{L_s} v_{mq} + \frac{1}{L_s} v_{gq} \end{aligned}$$

Using the power equality on both sides of the converter, we get (3):

(3) $$P_{dc} = P_{ac} \rightarrow V_{dc} I_{dc} = \frac{3}{2}\left(v_{gd} i_{sd}\right)$$

The fundamental component of the AC bus voltage is v_{gq} aligned with the d axis of the d-q synchronous reference frame. The global continuous-time equivalent mathematical model of an HVDC station is written as:

(4) $$\begin{aligned} \frac{di_{sd}}{dt} &= -\frac{R_s}{L_s} i_{sd} + \omega i_{sq} - \frac{1}{L_s} v_{md} + \frac{1}{L_s} v_{gd} \\ \frac{di_{sq}}{dt} &= -\omega i_{sd} - \frac{R_s}{L_s} i_{sq} - \frac{1}{L_s} v_{mq} \\ \frac{dV_{dc}}{dt} &= \frac{3 v_{gd}}{2C} \frac{i_{sd}}{V_{dc}} - \frac{1}{C} I_l \end{aligned}$$

where: i_{sd}, i_{sq}, V_{dc} The state variables ; v_{md}, v_{mq} The control variables ; v_{gd}, I_l The externals signals

Fuzzy sliding mode controller design

The structure of the FSMC proposed is presented in figure (2).

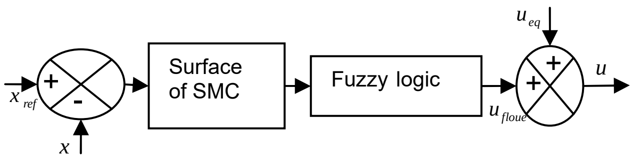

Fig.2. Proposed FSMC controller design

The principle of the fuzzy sliding mode control consists in determining the equivalent control in the same way developed in the case of the classic sliding mode controller[21].

The discontinuous part is replaced by a fuzzy logic controller. The global control law becomes[22]:

(5) $$u = u_{eq} + u_{floue}$$

The surface of sliding mode S and the change of sliding mode surface $\dot{S}$ and the control output as u_{flou}. Those are the input and output of the fuzzy controller[23].

A sliding proportional + integral (PI) surface in the space of error can be characterized as (6) [24]:

(6) $$S(t) = K_1 e(t) + K_2 \int_0^t e(t) d\tau$$

The K_1 and K_2 are positive constant

In this work, a Mamdani-type FLC is used. A set of seven membership functions (Figure 2, 3) with forty-nine rules are used (Table1). The linguistic variables are defined as: negative big (NB), negative medium (NM), negative small (NS), zero (ZO), positive small (PS), positive medium (PM), and positive big (PB)[25] [26].

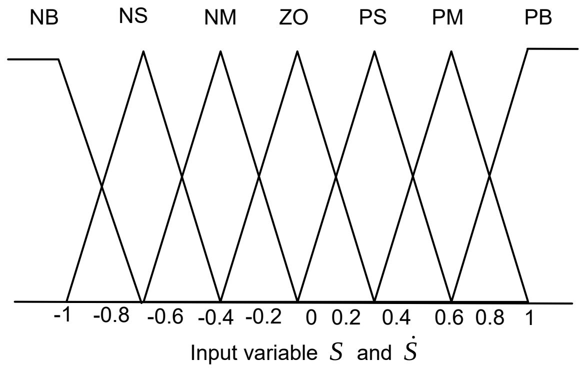

Fig.3. Membership functions for S and $\dot{S}$

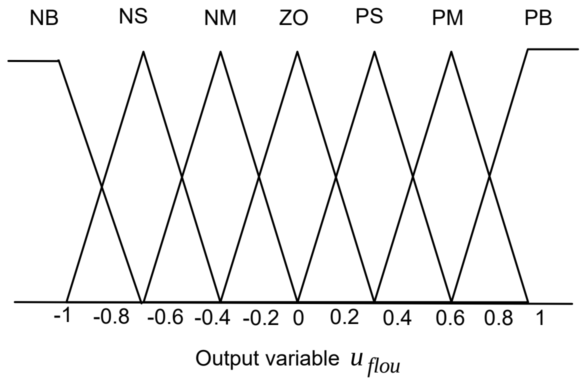

Fig.4. Membership functions for u_{flou}

Table 1. The Rule Base of FLC

u_{flou}		S						
		NB	NM	NS	ZO	PS	PM	PB
$\dot{S}$	NB	NB	NB	NB	NB	NM	NS	ZO
	NM	NB	NB	NB	NM	NS	ZO	PS
	NS	NB	NB	NM	NS	ZO	PS	PM
	ZO	NB	NM	NS	ZO	PS	PM	PB
	PS	NM	NS	ZO	PS	PM	PB	PB
	PM	NS	ZO	PS	PM	PB	PB	PB
	PM	ZO	PS	PM	PB	PB	PB	PB

The fuzzy output u_{flou} can be calculated by Defuzzification as follows:

(7) $$u_{flou} = \frac{\sum_{i=1}^{m} \mu_B\left(u_i(t)\right) u_i}{\sum_{i=1}^{m} \mu_B\left(u_i(t)\right)}$$

Fuzzy sliding mode control of VSC-HVDC system

In the present work, the conventional PI-type controllers have been replaced by FSMCs. The aim is to set the DC bus voltage V_{dc} and the reactive power Q_g to their reference values $V_{dc}{}^{ref}$ and Q^{ref} stations.

The block diagram of the control structure by FSMC proposed is presented in Figure (5):

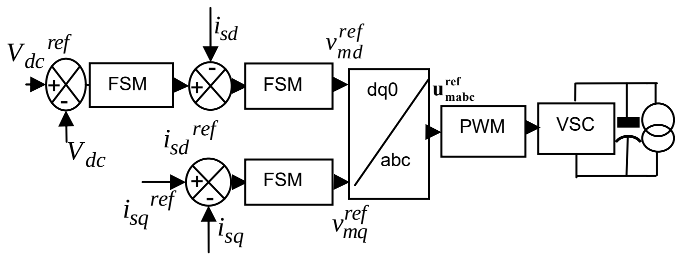

Fig.5. block diagram of FSMC-based VSC-HVDC station

The third equation for system (4) is used to control DC voltage V_{dc} where the current $i_{sd}{}^{ref}$ is chosen as a control variable.

The surface is chosen as:

(8) $$S_{Vdc} = K_1\left(V_{dc}{}^{ref} - V_{dc}\right) + K_2\int\left(V_{dc}{}^{ref} - V_{dc}\right)dt$$

During sliding mode, we have:

(9) $$\dot{S}_{V_{dc}} = 0$$

Substituting the value of the derivative of the DC voltage into equation (8) we get:

(10) $$i_{sd}{}^{ref} = V_{dc}\left(i_l + C_s * \left(\dot{V}_{dc}^{ref} + \frac{K_2}{K_1}\left(V_{dc}^{ref} - V_{dc}\right)\right)\right) - Ksign\left(S_{Vdc}\right)$$

Where K_1, K_2, K are positive constant.

The both sliding surfaces for the direct and the quadratic components $\mathbf{i_{sdq}}$ are defined as follows:

(11) $$\boldsymbol{S} = \mathbf{K_p e} + \mathbf{K_i}\int \mathbf{e}dt$$

Where

$$\boldsymbol{S} = \begin{bmatrix} S_d \\ S_q \end{bmatrix}; \mathbf{e} = \mathbf{i_{sdq}}^{\mathbf{ref}} - \mathbf{i_{sdq}}; \mathbf{K_p} = \begin{bmatrix} k_{psd} & 0 \\ 0 & k_{psq} \end{bmatrix};$$

$$\mathbf{K_i} = \begin{bmatrix} k_{isd} & 0 \\ 0 & k_{isq} \end{bmatrix}$$

By derivate the surface $\mathbf{S}$ chosen, we obtain (12):

(12) $$\dot{\mathbf{S}} = \mathbf{K_p}\dot{\mathbf{e}} + \mathbf{K_i e} = \mathbf{0}$$

By writing the first and the second equations written in (4) as (13):

(13) $$\dot{\mathbf{i}}_{\mathbf{sdq}} = \mathbf{A} * \mathbf{i_{sdq}} + \mathbf{B} * \mathbf{v_{mdq}} - \mathbf{M}$$

Where:

$$\mathbf{i_{sdq}} = \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix}, \mathbf{A} = \begin{bmatrix} -\frac{R_s}{L_s} & \omega \\ -\omega & -\frac{R_s}{L_s} \end{bmatrix}, \mathbf{B} = \begin{bmatrix} -\frac{1}{L_s} & 0 \\ 0 & -\frac{1}{L_s} \end{bmatrix},$$

$$\mathbf{M} = \begin{bmatrix} \frac{v_{gd}}{L_s} \\ 0 \end{bmatrix}$$

The resolution of the equation (13) gives the expression of the equivalent control as follows:

(14) $$\mathbf{u_{eq}} = \begin{bmatrix} v_{md} \\ v_{mq} \end{bmatrix} = \left(\mathbf{K_p}\right)^{-1}\begin{bmatrix} \mathbf{K_i e} + \\ \mathbf{K_p}\left(-\mathbf{A i_{sdq}} - \mathbf{M} + \dot{\mathbf{i}}_{\mathbf{sdq}}^{\mathbf{ref}}\right) \end{bmatrix}$$

Finally, the global control law is determined from the equations (15) (16):

(15) $$v_{md}{}^{ref} = -R_s i_{sd} + \omega L_s i_{sq} + v_{gd} - L_s \dot{i}_{sd}^{ref} - \frac{k_{isd}}{k_{psd}} L_s\left(i_{sd}{}^{ref} - i_{sd}\right) - k_d sign\left(S_{sd}\right)$$

(16) $$v_{mq}^{ref} = -R_s i_{sq} - \omega L_s i_{sd} - L_s \dot{i}_{sq}^{ref} - \frac{k_{isq}}{k_{psq}} L_s\left(i_{sq}^{ref} - i_{sq}\right) - k_q sign\left(S_{sq}\right)$$

The FSMC is applied to the DC bus voltage control. Its output is the current reference $i_{sd}{}^{ref}$. The latter is calculated by the equation (17)

(17) $$i_{sd}{}^{ref}(k) = i_{sd}{}^{ref}(k-1) + G_{i_{sd}}\Delta i_{sd}{}^{ref}(k)$$

For current adjustment, conventional PI regulators are replaced by fuzzy regulators with the elimination of the voltage compensation part, fuzzy current regulators are synthesized in the same way as the DC voltage regulator and their outputs v_{md} and v_{mq} are given by equations (18) and (19):

(18) $$v_{md}(k) = v_{md}(k-1) + G_{v_{md}}\Delta v_{md}(k)$$

(19) $$v_{mq}(k) = v_{mq}(k-1) + G_{v_{mq}}\Delta v_{mq}(k)$$

Simulation result and discussion

The simulation study, presented in this section, evaluates the control performances of a VSC-HVDC station model shown in Fig.1, using different controllers. A comparison study between the proposed FSM controller and PI, FL, SM controllers is presented.

a. DC step

Initially, the system is set to: $V_{dc}{}^{ref} = 1pu$. At t=0.7s, an evolution of 5% on $V_{dc}{}^{ref}$ and -10% Q^{ref} are applied.

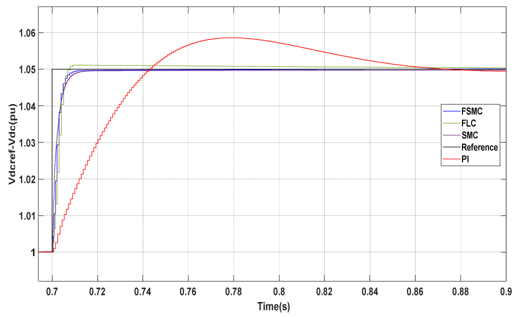

Fig.6. evolution of V_{dc} for step of 0.05 pu on $V_{dc}{}^{ref}$

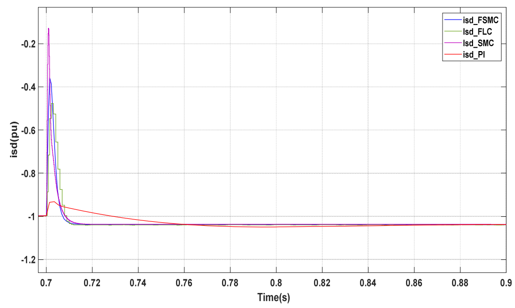

Fig.7. Current i_{sd} (pu)

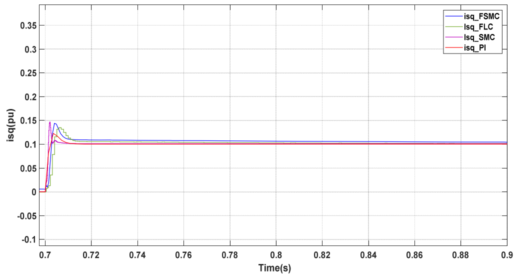

Fig.8. Current i_{sq} (pu)

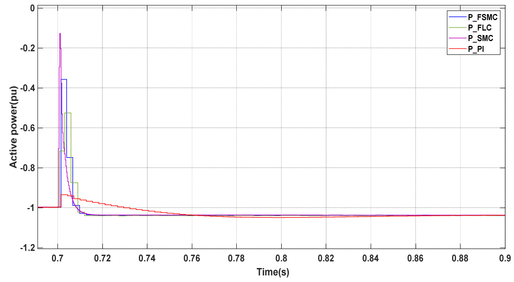

Fig.9. Active power (pu)

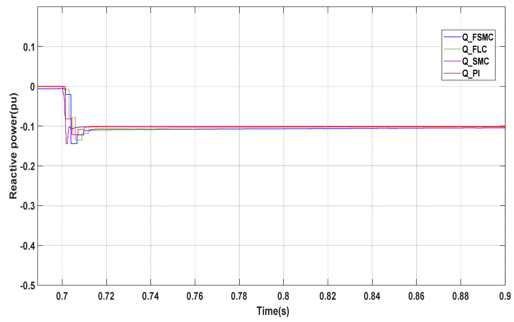

Fig.10. Reactive power (pu)

Figures (6, 7, 8, 9 and 10) illustrate that the transient overshoot is significantly reduced, compared to classical controller PI, by the application of fuzzy logic, sliding mode and the combination of the two approaches. The peak converges very fast for FSMC. In this method, the chattering in sliding mode is eliminated by the application of the fuzzy logic that explains the effective result obtained.

b. Voltage Drop And Swell

In order to verify the robustness of the proposed control method under drop and swell voltage, at t=0.6s, we inject a voltage disturbance of 0.01s in the AC network.

Figures (10 and 11) show the variation of V_{dc} voltage with the application of PI, FL, SM and FSM control methods. It converges very fast for FSMC method compared to the classical Pi, FL and SM controllers.

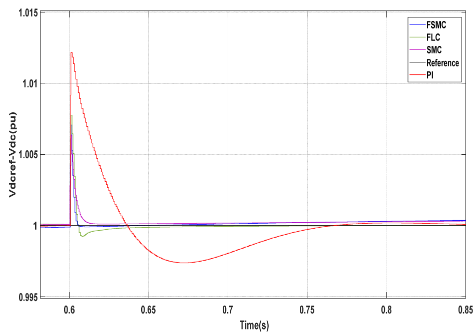

Fig.11. evolution of V_{dc} for a voltage drop of 0.05 pu in the AC side

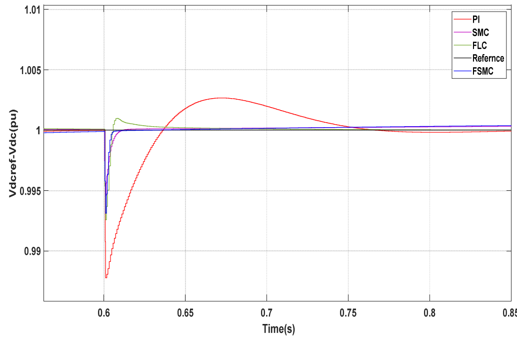

Fig.12. evolution of V_{dc} under voltage Swell of 0.05 pu in AC side

c. Frequency drop

We inject a frequency drop of 0.05 pu, at t=0.6s. The following figure shows the efficiency of the proposed control method for this frequency disturbance.

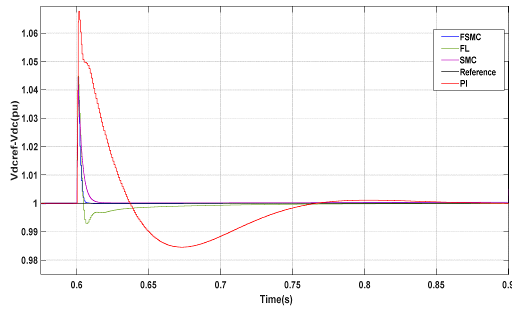

Fig.13. evolution of V_{dc} for frequency drop of 0.05 *pu*

Conclusion

In this paper, an intelligent fuzzy sliding mode controller for a VSC-HVDC system is presented. It has been employed to improve the performance of a sliding mode controller. The proposed intelligent controller was tested for a VSC converter operating in DC mode. The comparison of performance with the conventional PI, SM, FL controllers presented shows the efficiency of the proposed controller. It provides a much faster settling time, and lower overshoot, resulting in better stability and robust control performance.

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REFERENCES

[1] Poullain.S, Héliodore.F, Henni.A, J. L. Thomas, and E. Courbon, "Modelling of the dynamic characteristics of the DC line for VSC transmission scheme," *IEE Conf. Publ*, (2002), no. 485,pp. 305–310.
[2] Imdadullah, B. Alamri, M. A. Hossain, and Jamil Asghar .M. S "Electric power network interconnection: A review on current status, future prospects and research direction," *Electron.*, vol. 10,(2021) , no. 17, pp. 1–29.
[3] Parveen.S *et al.*, "The possibility of enhanced power transfer in a multi-terminal power system through simultaneous ac–dc power transmission," *Electron.*, vol. 11,(2022), no. 1.
[4] Eyenubo.O and Oshevire.P, "Improvement of Power System

Quality Using Vsc-Based Hvdc Transmission,” *Niger. J. Technol.*, vol. 36,(2017) , no. 3, pp. 889–896.
[5] Ayari.M, Belhaouane. M. M, N. B. Braiek, and X. Guillaud, “Optimal control design for VSC-HVDC systems,” *2013 Int. Conf. Electr. Eng. Softw. Appl. ICEESA (2013)*, pp. 1–6.
[6] Belhaouane. M. M, Ayari.M, Benhadj Braiek.N, and X. Guillaud, “Nonlinear modeling and control of a VSC-HVDC transmission systems,” *24th Mediterr. Conf. Control Autom. MED 2016*, pp. 701–706.
[7] Ramadan. H. S, Siguerdidjane.H, and Petit.M, “On the robustness of VSC-HVDC systems controllers Under parameters uncertainties,” *40th North Am. Power Symp. NAPS2008*, 2008.
[8] Ruan. S. Y, Peng. G. J. Li, L, Sun. Y. Z., and Lie. T. T, “A nonlinear control for enhancing HVDC light transmission system stability,” *Int. J. Electr. Power Energy Syst.*, vol. 29, (2007) , no. 7, pp. 565–570.
[9] Moharana.A and Dash. P. K, “Input-output linearization and robust sliding-mode controller for the VSC-HVDC transmission link,” *IEEE Trans. Power Deliv.*, vol. 25, (2010) , no. 3,pp. 1952–1961.
[10] Ayari.M, Belhaouane. M. M, Jammazi.C, Braiek. N. B., and Guillaud.X, “On the Backstepping Approach for VSC-HVDC and VSC-MTDC Transmission Systems,” *Electr. Power Components Syst.*, vol. 45,(2017) , no. 5, pp. 520–533.
[11] Ayari.M, Belhaouane. M. M, Jammazi.C, Braiek. N. B, and Guillaud.X, “Finite-time stabilisation of some power transmission systems,” *Trans. Inst. Meas. Control*, vol. 41, (2019) , no. 3, pp. 701–716.
[12] Baoquan, Jin, Liu Xin, and Zhang Hongjuan. "Improvement on performance of electro-hydraulic central position control system by adaptive reaching law sliding mode method." Przegląd Elektrotechniczny 90, no. 2 (2014): 146-148.
[13] Abdelkader, Belhachemi, and Belarbi Ahmed Wahid. "Modeling and control of photovoltaic system using sliding mode controle, comparative studies with conventional controls." Przegląd Elektrotechniczny 1, no. 2 (2020): 184-189.
[14] Kairous, Djilali, and Mustapha Benghanem. "Advanced Control Strategy based on second order sliding mode of DFIG for Power System Fault Ride Through." Przegląd Elektrotechniczny 97 (2021).
[15] Boudali, Abdelkader, Karim Negadi, Mohamed Boudiaf, Abderrahmane Berkani, and Fabrizio Marignetti. "Super Twisting Sliding Mode Controller of small hydropower plant energy generation based DFIG." Przegląd Elektrotechniczny 96 (2020).
[16] Nayak.N, Routray. S. K. R, and Rout. P. K, “Robust fuzzy sliding mode controller design for voltage source converter high-voltage DC based interconnected power system,” *Aust. J. Electr. Electron. Eng.*, vol. 11, (2014) , no. 4, pp. 421–433,.
[17] Ahmed.H, “Controlling of D . C . Motor using Fuzzy Logic Controller,” *Conf. Adv. Commun. Control Syst. 2013 (CAC2S 2013)*, vol. 2013, no. Cac2s, (2013),pp. 666–670,.
[18] Castro. J. L, “Fuzzy Logic Controllers Are Universal Approximators,” *IEEE Trans. Syst. Man. Cybern.*, vol. 25, , (1995) ,no. 4, pp. 629–635.
[19] Shen.H, Iorio.J, and Li.N, “Sliding mode control in backstepping framework for a class of nonlinear systems,” *J. Mar. Sci. Eng.*, vol. 7,(2019) , no. 12,pp. 30–34.
[20] Ayari.M, Ghariani. M. A, Belhaouane. M. M, and Benhadj Braiek.N, “Integral backstepping control design for VSC-HVDC systems,” *STA 2014 - 15th Int. Conf. Sci. Tech. Autom. Control Comput. Eng.*, no. March(2016), pp. 698–703.
[21] Zeb.K *et al.*, “Design of fuzzy-PI and fuzzy-sliding mode controllers for single-phase two-stages grid- connected transformerless photovoltaic inverter,” *Electron.*, vol. 8, (2019) , no. 5,pp. 1–19.
[22] Banrejee.A and Nigam. M. J, “Designing of proportional sliding mode controller for linear one stage inverted pendulum,” *Adv. Electr. Electron. Eng.*, vol. 9,(2011) , no. 2, pp. 84–89.
[23] Behnamgol.V and Vali. A. R, “Terminal sliding mode control for nonlinear systems with both matched and unmatched uncertainties,” *Iran. J. Electr. Electron. Eng.*, vol. 11,(2015) , no. 2, pp. 109–117.
[24] Bandal.V. S, “a Literature Review Multi-Level Inverter Topologies and Sliding Mode Control Strategies,” vol. 3, (2017) , no. 4, pp. 16–40.
[25] Al Gizi.A, Mustafa.M, Alsaedi. M. A, and Zreen.N, “Fuzzy control system review,” *Int. J. Sci. Eng. Res.*, vol. 4, (2013), no. 1, pp. 1–8.
[26] Malhotra.R, Singh.N, and Singh.Y, “Fuzzy Logic Modelling , Simulation and Control : A Review,” *Rev. Lit. Arts Am.*, vol. 4333 ,(2010), pp. 183–188.