Enhancing Power Grid System Analysis with Medium Voltage Cascaded H-Bridge Motor Driver Dynamic Model

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Abstract: - Medium voltage cascaded H-Bridge motor drives (MV-CHBMD) are popular with renewable applications because of their scalability, reliability, and modularity. The MV-CBHMDs are used in different medium voltage applications and significantly affect grid flexibility, performance, and efficiency. Even with the famous use of MV-CHBMD, the provided simulation models need to be more detailed to cover grid connection dynamic investigations. This study provides a dynamic design of MV-CHBMD, connected with the power grid source and induction motor (IM) with load, which provides a compliance large-scale analysis for the dynamic act of the power grid system. The proposed model of dynamic MV-CHBMD is suitable for power system studies. The model provides an analytical analysis of the grid connection with the cascaded H-bridge motor driver (CHBMD) and IM on the load side of the driver. It accurately represents the dynamic of the total system under different disturbances. The main factors affected during any perturbation are variable frequency and voltage, which are deeply considered in the proposed model. A simulation analysis verifies the model's accuracy, reliability, and effectivity. The mode sensitivity analysis depends on the impact of the variable parameters on the system acting and responding. The proposed model is easily insertable in the extensive grid-simulating system, which provides more accurate results in power grid dynamic studies.

Key-Words: - Medium Voltage Systems, Cascaded H-Bridge, Motor Driver, Dynamic Studies, Simulation Analysis, Optimized Design.

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1 Introduction

For more than three decades, representing power grid systems has been recognized, which helps to study the performance of different factors that impact power system stability. CHBMD system provides complete control of torque and speed of the IM by converting voltage and frequency to controllable values. In high-power applications requiring medium voltage levels, CHBMD delivers the same output power but with a lower current. As the grid is operated and designed to be stable on a specific margin, all connected device simulation models are essential to overall system expectations under critical situations, [1]. Despite the big efforts of scientists and researchers' system simulation modelling is not enough to cover all new types of loads and the effect of each load on the grid efficiency, [2]. The CHBMD with IM combination is a widely used application in the industrial sector as sequence modelling driver and motor combination become more essential because of the enormous increase in usage level in the systems over time. The averaged-value dynamic model of a three-phase voltage system connected with an inverter is presented using differential equations in [3]. The model, [4], is only for the inverter, but the other components, like the multi-pulse transformer, rectifier system, DC link and IM load, are not included in the model, [5]. Although MATLAB/Simulink has a standard library with some detailed models of different components, but it is not usable in significant simulation software of grids, [6]. To fill the MV-CHBMD modelling gap authors in [7], present propose a "linearization approach" method. The [8], model was improved by transferring the mathematical reaction of a low-voltage system, [9]. In real life, VM-CHBMDs will disconnect from the grid automatically when big disturbances at the same time they are capable of handling small disturbances. The proposed model perfectly fits minor disturbances in the power system, so it can test minor disturbances and analyze them to get stability of the system. Therefore, the MV-CHBMD model can improve the system functions, [10], [11]. Using the proposed model in big system analyses helps to understand the transfer function, the behaviors of each component and its reaction to various disturbances in the grid. it is also easy to implement on big simulations of the power grid, [12].

2 Study and Analysis of MV-CHBMD Model

The MV-CHBMD is the famous topology for medium voltage applications especially with high-speed and big scales motors, [13]. The CHBMD structure consists of many power cells operating in low voltage and high current power electronics. By connecting the power cells in series higher voltage could be obtained example two power cells per phase in the five-level driver, three cells per phase in the seven-level driver and four cells per phase in the nine-level driver, [14]. The seven-level VM-CHBMD has three power cells per phase, so in total, it has nine power cells and can produce more than 1,4 kV at the output side. Figure 1 shows the proposed eighteen-pulse transformer, seven-level MV-CHBMD structure with its nine power cells, and IM.

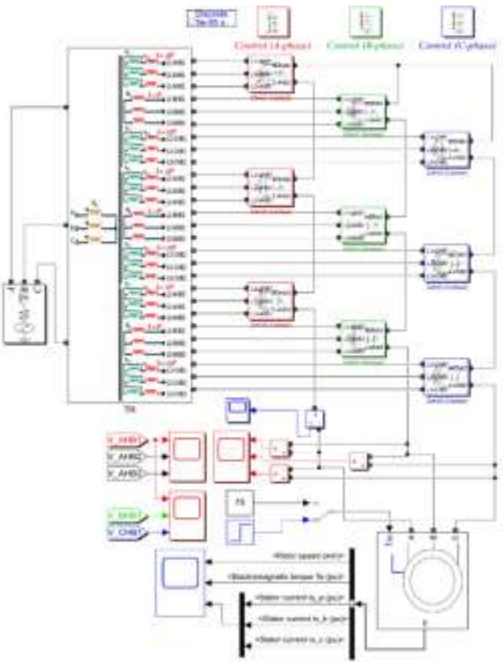

Fig. 1: The seven-level VM-CHBMD System

Each power cell has a unique PWM control signal, to control its H bridge power electronic switches. The power flows through a multi-pulse transformer to the rectifier system in each power cell, which delivers current to the DC link, then to the H bridge at the endpoint power cells connected in series to the IM. Each pulse of the eighteen-pulse transformer provides a 480V AC, [15]. The pulses of the transformer are connected to the power cells which have the rectifier system, DC link and full bridge of power electronic switches. The rectifier system supplies 640Vdc to the DC link, which is connected to the motor through the switches. The power electronic switches operate according to the control signals.

2.1 Analytic Model of Power Cell

The DC link has no shifts, so there is no effect on the phase shifting of the multi-pulse transformer, as the rectifier system converts the alternative current to direct current, [15]. The output voltage (V0) of a single power cell can be calculated using (1) equation. The E_{dc} refers to voltage of DC link. The C is referring to duty cycle, [16].

$$V_0 = C * E_{dc} \tag{1}$$

The IM phases voltage calculated by (2) equations.

$$\left.\begin{aligned} V_{an} &= \left(\frac{n_p}{6}\right) V_0 \cos(\omega_s t) \\ V_{bn} &= \left(\frac{n_p}{6}\right) V_0 \cos(\omega_s t - \tfrac{2\pi}{3}) \\ V_{cn} &= \left(\frac{n_p}{6}\right) V_0 \cos(\omega_s t + \tfrac{2\pi}{3}) \end{aligned}\right\} \tag{2}$$

The np refers to the number power cells used in MV-CHBMD. The ω_s is referring to the electrical field speed in the stator of IM. The abc sequence is not usable in control algorithms because that is covered to dq0 as shown in equation (3). The v_{qs} refers to the terminal voltage at the IM in the quadrature -axis, and the same v_{ds} refers to the direct-axis.

$$\left.\begin{aligned} V_{qs} &= \left(\frac{n_p}{6}\right) V_0 \\ V_{ds} &= 0 \end{aligned}\right\} \tag{3}$$

The actual power from the driver to IM (P_{ac-IM}) is calculated using equation (4).

$$P_{ac-IM} = \frac{3}{2}\left(V_{ds} i_{qs} + V_{qs} i_{qs}\right) = \left(\frac{n_p}{4}\right) V_0\, i_{qs} \tag{4}$$

The iqs and ids refer to the current of the stator of IM. The DC link power ($P_{dc-link}$) for all power cells in the driver is related to the actual power of the driver, as shown in equation (5).

$$P_{dc-link} = \left(\frac{n_p}{2}\right) V_0 \, i_I \tag{5}$$

The i_I refers to the per power cell input dc current. The i_d refers to the current at the driver output and it calculated using i_I, Edc and $C_{dc\text{-}link}$ capacitor as shown in equation (6).

$$i_d = i_I + C_{dc-link} \frac{dE_{dc}}{dt} \tag{6}$$

Assuming there are no power losses in connection points and power electronic switches, the actual power of the driver is equal to the DC link power. As a result, the relation between the per power cell input dc link current and the current of the stator of IM is calculated after applying Laplace Transform as shown in equation (7), [17].

$$\Delta i_{qs} = \frac{2}{d_0} \Delta i_d - \frac{i_{qs0}}{d_0} \Delta d - \frac{2C_{dc-link}}{d_0} S \, \Delta E_{dc} \tag{7}$$

2.2 Analytic Model of Power Cell

The MV-CHBMD control algorithm utilizes the close loop method, and for another control methods, the user needs to improve or develop the mathematical model for it. The duty cycle is important to obtain the driver position to get the motor synchronous and the voltage at the quadrature-axis. The duty cycle and voltage of the IM in the quadrature and direct axis's relation are explained by equation (8), [18].

$$\begin{bmatrix} v_{qs}^{e*} \\ v_{ds}^{e*} \end{bmatrix} = \begin{bmatrix} \cos\theta_{ce} & \sin\theta_{ce} \\ -\sin\theta_{ce} & \cos\theta_{ce} \end{bmatrix} \begin{bmatrix} v_{qs}^{e} \\ v_{ds}^{e} \end{bmatrix} \tag{8}$$

The θ_{ce} refers to the angel between the reference displacement of CHBMD and the synchronous reference. The closed-loop control algorithm calculated by equations (9), (10), (11), (12) and (13).

$$\omega_{SL} = K_{pm}(\omega_r^* - \omega_r) + \int_0^t K_{im}(\omega_r^* - \omega_r)dt + (\omega_{s0} - \omega_{r0}) \tag{9}$$

$$\omega_s = \omega_{SL} + \omega_r \tag{10}$$

$$d = \sqrt{2} \frac{\omega_s(\frac{V_b}{\omega_s})}{\frac{n_p}{6}} \tag{11}$$

$$v_{qs}^{e*} = \sqrt{2}\, \omega_s (\frac{V_b}{\omega_b}) \tag{12}$$

$$v_{ds}^{e*} = 0 \tag{13}$$

The K_{pm} and K_{im} refer to the proportional and integral of speed controller PI, respectively. The V_b refers to the phase voltage of IM. The ω_r refers to IM rotor electrical angle. The ω_{SL} refers to a slip of electrical angle. The star next to the variable refers to the reference value, and the parameters have a 0 referring to initial values. The value of ω_r calculated by solving equation (10), as shown in equations (14), [19].

$$\Delta\omega_s = \frac{1 - K_{pm} - K_{im}}{S} \Delta\omega_r \tag{14}$$

The value of i_{rqs} calculated by solving equation (7), as shown in equations (15) and (16), [20].

$$\Delta d = \left(\frac{\sqrt{2}\, V_b \omega_{s0}}{\frac{n_p}{6} \omega_b E_{dc0}^2}\right) \Delta E_{dc} + \left(\frac{\sqrt{2}\, V_b}{\frac{n_p}{6} \omega_b E_{dc0}}\right) \Delta E_{dC} \tag{15}$$

$$\Delta i_{qs} = \frac{2}{d_0} \Delta i_d - \frac{\sqrt{2}\, V_b i_{qs0}}{\frac{n_p}{6} \omega_b E_{dC0} d_0} \Delta\omega_s + \left(\frac{\sqrt{2}\, V_b \omega_{s0} i_{qs0}}{\frac{n_p}{6} \omega_b E_{dc0}^2 d_0} - \frac{2C_{dc-link}}{d_0} S\right) \Delta E_{dc} \tag{16}$$

The value of V_{qs} calculated by solving equations (3) and (17), as shown in equation (18), [21].

$$\Delta V_{qs} = \left(\frac{n_p}{6}\right) d_0 \Delta E_{dc} + \left(\frac{n_p}{6}\right) \Delta E_{dc} \Delta d \tag{17}$$

$$\Delta V_{qs} = \left(\frac{n_p}{6}\right) d_0 \Delta E_{dc} + \left(\frac{n_p}{6} \Delta E_{dc}\right) \left(\left(\frac{\sqrt{2}\, V_b \omega_{s0}}{\frac{n_p}{6} \omega_b E_{dc0}^2}\right) \Delta E_{dC} + \left(\frac{\sqrt{2}\, V_b}{\frac{n_p}{6} \omega_b E_{dco}}\right) \Delta E_{dC} \right) \tag{18}$$

2.3 Dynamic Model Deriving of CHBMD

The total actual power of the MV-CHBMD system (P_{ac}) is the sum of the actual power of each power cell divided by two. It is the same for total reactive power (Q_{ac}). Accordingly, the (Pac) and (Q_{ac}) of seven levels MV-CHBMD calculated as per equations (19) and (20), respectively.

$$P_{ac} = \frac{27}{4}(V_{dg} i_{dg} + V_{qg} i_{qg}) \tag{19}$$

$$Q_{ac} = \frac{27}{4}(-V_{dg} i_{qg} + V_{qg} i_{dg}) \tag{20}$$

The overall equation of MV-CBHMD is calculated by combining all the differential equations of the system compensation, as shown in equations (21) and (22), [20].

$$P = P_0 + G_{P1}\Delta E_{dc} + G_{P2}\Delta E_{dc}{}^2 + (G_{P3} + G_{P4}\Delta E_{dc})\Delta f_g \tag{21}$$

$$Q = Q_0 + G_{Q1}\Delta E_{dc} + G_{Q2}\Delta {E_{dc}}^2 + (G_{Q3}+G_{PQ4}\Delta E_{dc})\Delta f_g \quad (22)$$

The parameters G_{Pi} and G_{Qi} refer to are the 7th-order functions. All equations obtained were converted to a code in the MATLAB environment. The user can change the parameter to obtain different result, according to, their own system requests, [22]. The IM parameters are 1500HP, 2300V, 50Hz, 0.035Ω, 0.002H, 1800 RPM, and1500Nm. The CHBMD parameters are 10e-3F, 1.3V for diode, 50 Hz, K_{pm}=9 and K_{im} =10. Power source parameters are 480V, 1.2mH and 50Hz.

3 The CHBMD Model Verification

The verification of the proposed model was conducted by MATLAB simulation of medium voltage CHBMD seven-level, connecting with the grid through eighteen pulse transformer, and induction motor. The control method is PWM-enhanced algorithm. The output of the simulation model will compare with the standard MATLAB models, to show the reaction of the developed model. The mode takes dependence voltage and frequency under consideration. The dynamic acting of the models under different situations of disturbances will be analyzed.

To confirm the voltage reliance of the provided model, three controlled faults are applied to the input side of the CHBMD model, which reduces the voltage by 90%. The fault begins at 3.3 s and ends at 3.9 s. The total simulation duration is 4 seconds. Figure 2 shows the dynamic reaction of the actual power in the simulation model under voltage changes. It clearly verified the accuracy of the proposed model according to the actual power under voltage disturbances. The actual system varies under voltage changes. Thus, it is not easy to presume CHBMD as constant load.

To study the frequency performance of the proposed model, a frequency value change between 52.5 Hz to 47.5 Hz is applied at the grid source. This frequency validation starts at 3.3 s and ends at 3.9 s. Figure 3 shows the dynamic reaction of the actual power in the simulation model under frequency changes. It clearly verified the accuracy of the proposed model according to the actual power under frequency disturbances.

After studying and confirming the sensitivity of the proposed model in disturbances situations of voltage and frequency, the accurate study of the proposed model is done by analyzing the system response in different situations like changes in motor torque, the value of DC link capacitance, and the PI controller parameters.

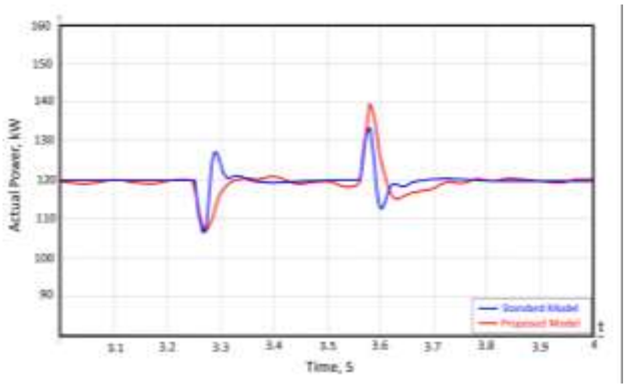

Fig. 2: Reaction of Proposed Model under Voltage disturbances

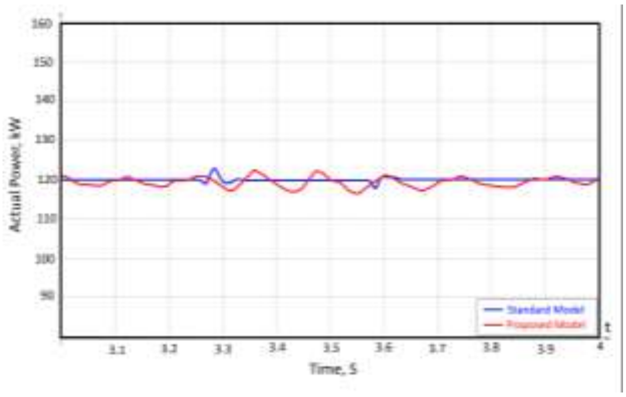

Fig. 3: Reaction of Proposed Model under Frequency disturbances

Three study cases were considered to study the MV-CHBMD system sensitive to torque changing. The three statuses are 75%, 100%, and 125% loading to the motor. Figure 4 shows the proposed model responses under torque changing.

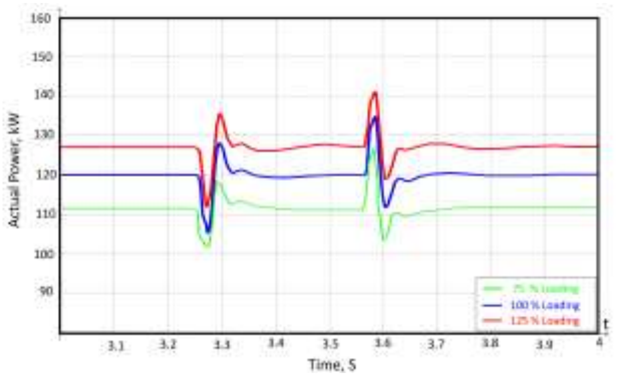

Fig. 4: Reaction of Proposed Model under torque changing

It clearly verified the accuracy of the proposed model according to the actual power under torque changing. The simulated results show the load significantly affects steady and responses for the actual power. Three cases were considered to study the MV-CHBMD system sensitive to changing DC link capacitance values. The three values of DC link capacitance are 9.2mF, 10mF, and 18mF. Figure 5 shows the proposed model responses under DC link capacitance different values.

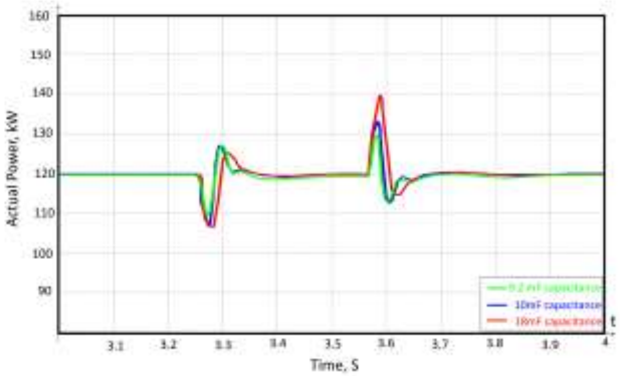

Fig. 5: Reaction of Proposed Model under DC link capacitance different values

It clearly verified the accuracy of the proposed model according to the actual power under DC link capacitance different values. Three cases were considered to study the MV-CHBMD system sensitive to changing PI controller parameters. The three values of PI controller parameters are (K_p=1.25 & K_m=1.26), (K_p=8 & K_m=9), and (K_p=0.25 & K_m=0.02). Figure 6 shows the proposed model responses under PI controller parameters with different values.

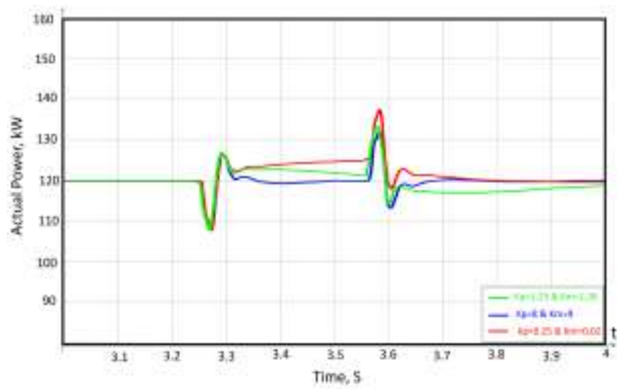

Fig. 6: Reaction of Proposed Model under PI controller parameters different values

It clearly verified the accuracy of the proposed model according to the actual power under PI controller parameters with different values. The proposed model can recover after a short time of disturbances and back to steady-state values. it is essential to use specific PI controller parameters for the model, otherwise, the model will not back to the steady status after big disturbances, therefore, the results of the simulation will not match the actual results.

4 Conclusion

The accurate analysis of the proposed model shows that critical parameters of the system have a significant effect on the overall response and reaction of the model. The user should take into consideration the system parameters' impact, operating situation, and disturbances limits when creating its own model. If it is not provided, it could be assumed the closest value possible to actual value. The MV-CHBMD model system is proposed in this work using the mathematical equation. The Model sensitivity is confirmed by applying different situations, like voltage and frequency disturbances. The most important parameters that affect the stability of the system are evaluated and analyzed with various values, which confirm the model's accurately and sensitivity. The proposed model has the perfect ability to implement in the big system simulation results without any effect on the accuracy or the memory of used software due to its low space program.

References:

[1] X. Liang and W. Xu, "Modeling variable frequency drive and motor systems in power systems dynamic studies," 2013 IEEE Industry Applications Society Annual Meeting, Lake Buena Vista, FL, 2013, pp. 1-11, doi: 10.1109/IAS.2013.6682607.

[2] H. Atighechi, S. Chiniforoosh, and J. Jatshevich, "Approximate Dynamic Average-Value Model for Controlled LineCommuted Converters", 24th Canadian Conference on Electrical and Computer Engineering (CCECE) 2011, Niagara Falls, Page(s): 966-970.

[3] A. Alahmad and F. Kaçar, "Simulation of Induction Motor Driving by Bridge Inverter at 120°, 150°, and 180° Operation," 2021 8th International Conference on Electrical and Electronics Engineering (ICEEE), Antalya, Turkey, 2021, pp. 121-125, doi: 10.1109/ICEEE52452.2021.9415930.

[4] Y. Guan, Z.Q. Zh, u. I.A.A Afinowi, J.C. Mipo and P. Farah, "Difference in maximum torque-speed characteristics of induction machine between motor and generator operation modes for electric vehicle

application", Electric power system, vol. 136, pp. 406-414, July 2016.

[5] Y. Li, Y. Zhao and F. Diao, "High-Efficiency Model Predictive Control for Star-Connected Cascaded H-Bridge STATCOM Under Unbalanced Conditions," 2020 IEEE Applied Power Electronics Conference and Exposition (APEC), New Orleans, LA, USA, 2020, pp. 982-988, doi: 10.1109/APEC39645.2020.9124355.

[6] T. Dharanirajan, K. Gowri Sankar, K. Surya Kumar and G. Renukadevi, "OPEN LOOP RESPONSE OF INVERTER-FED THREE-PHASE INDUCTION MOTOR DRIVE", International Journal of Electrical and Electronic Engineering & Telecommunications, vol. 1, no. 1, pp. 148-153, March 2015.

[7] A. Alahmad and F. Kaçar, "Medium-Voltage (MV) Motor Drives Topologies and Applications," 2022 International Conference on Electrical, Computer and Energy Technologies (ICECET), Prague, Czech Republic, 2022, pp. 1-5, doi: 10.1109/ICECET55527.2022.9872584.

[8] V. M. R. de Oliveira, R. S. Camargo, E. J. B. Peña and L. F. Encarnação, "Transformeless Cascaded H-Bridge Back-to-Back Converter Driving an Dynamic Load," 2020 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe), The Hague, Netherlands, 2020, pp. 136-140, doi: 10.1109/ISGT-Europe47291.2020.9248856.

[9] A. Marzoughi, R. Burgos, D. Boroyevich and Y. Xue, "Design and comparison of cascaded h-bridge modular multilevel converter and 5-l active neutral point clamped topologies for motor drive applications", IEEE Trans. on Ind. Appl., vol. 54, no. 2, pp. 1404-1413, March 2018.

[10] H. Merabet, T. Bahi, K. Bedoud and D. Drici, "Real-Time Switches Fault Diagnosis for Voltage Source Inverter Driven Induction Motor Drive", International Journal of Electrical and Electronic Engineering & Telecommunications, vol. 8, no. 2, pp. 103-107, March 2019.

[11] A. Alahmad, F. Kaçar, C. Polat Uzunoğlu, "Medium-Voltage Drives (MVD) - Performance Analysis of Seven-Level Cascaded H-Bridge Multilevel Driver," WSEAS Transactions on Electronics, vol. 14, pp. 57-64, 2023, DOI:10.37394/232017.2023.14.7.

[12] Vemana Arun Sai and K Vamshi Krishna Varma, "A NEW SINGLESTAGE MULTILEVEL TYPE FULL-BRIDGE CONVERTER APPLIED TO BRUSHLESS DC MOTOR", International Journal of Electrical and Electronic Engineering & Telecommunications, vol. 3, no. 1, pp. 62-74, January 2014.

[13] M. Lei, C. Zhao, Z. Li and J. He, "Circuit Dynamics Analysis and Control of the Full-Bridge Five-Branch Modular Multilevel Converter for Comprehensive Power Quality Management of Cophase Railway Power System," in IEEE Transactions on Industrial Electronics, vol. 69, no. 4, pp. 3278-3291, April 2022, doi: 10.1109/TIE.2021.3076720.

[14] K. Yang et al., "Unified Selective Harmonic Elimination for Multilevel Converters", IEEE Transactions on Power Electronics, vol. 32, no. 2, pp. 1579-1590, Feb. 2017.

[15] A. Alahmad, F. Kacar, & C. P. Uzunogl, "Optimum Design of an 18-Pulse Phase Shifting Autotransformer Rectifier to Improve the Power Quality of Cascaded H-Bridge Motor Driver," Elektronika Ir Elektrotechnika,vol. 29, pp12-18, 2023, https://doi.org/10.5755/j02.eie.35126.

[16] H. Taghizadeh and M. Tarafdar Hagh, "Harmonic Elimination of Cascade Multilevel Inverters with Nonequal DC Sources Using Particle Swarm Optimization", IEEE Transactions on Industrial Electronics, vol. 57, no. 11, pp. 3678-3684, Nov. 2010.

[17] H. Madani, H. M. Hesar and X. Liang, "Selective Harmonic Elimination in Cascade H-bridge Multilevel Voltage Source Inverters Using A Hybrid Optimization Algorithm," 2022 IEEE Electrical Power and Energy Conference (EPEC), Victoria, BC, Canada, 2022, pp. 13-17, doi: 10.1109/EPEC56903.2022.10000145.

[18] T. S. Babu, K. Priya and D. Maheswaran, "Selective voltage harmonic elimination in PWM inverter using bacterial foraging algorithm", Swarm and Evolutionary Computation, vol. 20, pp. 74-81, Feb. 2017.

[19] P. J. Gómez, L. Galván, E. Galván, J. M. Carrasco and S. Vázquez, "Optimal Switching Sequence Model Predictive Control for Single-Phase Cascaded H-Bridge," IECON 2021 – 47th Annual Conference of the IEEE Industrial Electronics Society, Toronto, ON, Canada,

2021, pp. 1-6, doi: 10.1109/IECON48115.2021.9589627.

[20] L. M. Muniz, M. J. Carmo, M. F. Santos, A. F. Santos Neto and P. Mercorelli, "Case Study: Aspects of Fuzzy Controller Implementation in Embedded Systems," 2020 International Conference on Mathematics and Computers in Science and Engineering (MACISE), Madrid, Spain, 2020, pp. 155-158, doi: 10.1109/MACISE49704.2020.00033.

[21] K. C. Costa, G. A. Machareth, M. F. Santos and P. Mercorelli, "Classical PI Controllers with Anti-Windup Techniques Applied on Level Systems: An Interesting Case Study," 2020 International Conference on Mathematics and Computers in Science and Engineering (MACISE), Madrid, Spain, 2020, pp. 163-166, doi: 10.1109/MACISE49704.2020.00035.

[22] K. K. Kumar, M. V. Karthik and K. V. Kumar, "THD Reduction in Single-Phase Cascaded H-Bridge Multilevel Inverter using Fuzzy Logic Controller," 2023 International Conference on Sustainable Computing and Smart Systems (ICSCSS), Coimbatore, India, 2023, pp. 1321-1327, doi: 10.1109/ICSCSS57650.2023.10169348.

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