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An improved modulation technique suitable for a three level flying capacitor multilevel inverter

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ABSTRACT

This research paper introduces an innovative modulation technique for controlling a 3-level flying capacitor multilevel inverter (FCMLI), aiming to streamline the modulation process in contrast to conventional methods. The proposed simplified modulation technique paves the way for more straightforward and efficient control of multilevel inverters, enabling their widespread adoption and integration into modern power electronic systems. Through the amalgamation of sinusoidal pulse width modulation (SPWM) with a high-frequency square wave pulse, this controlling technique attains energy equilibrium across the coupling capacitor. The modulation scheme incorporates a simplified switching pattern and a decreased count of voltage references, thereby simplifying the control algorithm.

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1. INTRODUCTION

Direct current (DC) power to alternating current (AC) power converters play a main role in different power system main parts: generation, transmission, distribution. These converters may also known as inverters. Moreover, inverters are widely used in electric vehicle drives, air conditioning, variable frequency drives, un-interruptible power supplies, high voltage DC power transmission, static var compensators, active filters, flexible AC transmission systems, and the use of DC power sources (such as electricity generated by fuel cells, solar panels, or batteries) [1], [2]. Inverters are classified based on the output shape for example: square wave inverters [3], two level inverters [4], and multilevel inverters [5].

Recently, multi-level inverters (MLIs) earned a lot of attention for their benefits in different power range applications [6]. Interestingly, MLIs can draw an input current with high power factor [7]. Also, they have the capability to reduce the voltage stress accross the semiconductor switches as MLIs utilized several switches in their construction [8]. Three primary topologies of multilevel inverters are: diode clamped MLIs [9], flying capacitor MLIs (FCMLIs) [10], and Cascaded H-Bridge MLIs [11]. This paper focuses on the flying capacitor multilevel inverters since it has lower number of diodes compared with diode clamped MLIs and overcome the voltage balance problem of other MLIs, see Figure 1. The N level FCMLI requires $(N-1)$ DC link capacitors, $2(N-1)$ switches and $(N-1)(N-2)/2$ auxiliary capacitors in each phase leg [12]. Therefore, a single phase 3-level FCMLI comprises of 2 DC link capacitors, 4 switches, and a single auxiliary capacitor as shown in Figure 1.

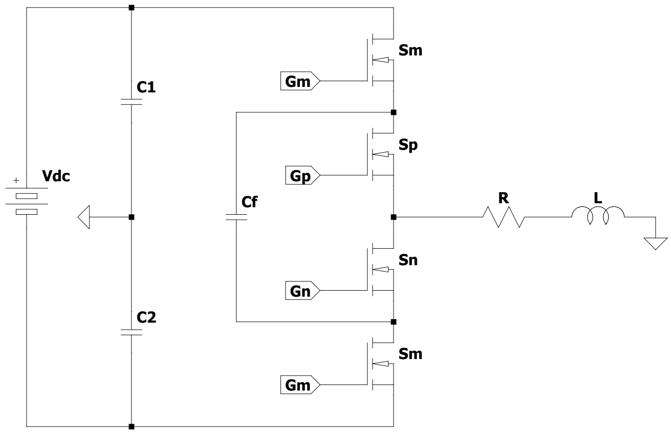

Figure 1. A single phase 3 level flying capacitor multilevel inverter

Many researches presented different control schemes of FCMLIs for example: in [13] authors proposed a generalized approach to pulse width modulation (PWM) for an infinite number of levels, based on the ideas of carrier swapping and phase shift. It offers a simple and straightforward technique for obtaining the switching states, their order, and the PWM pattern. A single-phase, seven-level Gallium-Nitride GaN inverter prototype was used for experimental testing while using MATLAB/Simulink. In [14] another level-shift PWM method used on the flying capacitor three-phase, five-level inverter was presented. The proposed inverter has a drawback of the suggested topology is the increased number of capacitors. 22 capacitors with 6 capacitors connected across the switches in each phase are used. The simulation was used to confirm the phase voltage, line voltage, and output voltage total harmonics distortion (THD).

The control of FCMLIs may also uses of model predictive control (MPC) because of its straightforward design, quick dynamic response, and accurate reference tracking. However, because it directly depends on the system's mathematical model to forecast the ideal switching states to be employed at the following sampling time, it suffers from parametric uncertainties [15], [16]. Uncertain parameters therefore result in an MPC that is poorly constructed. With a slight detrimental effect on the inverter's performance, this research provides a model-free control technique based on artificial neural networks (ANNs) to mitigate the consequences of parameter mismatching [17], [18].

Various types of multilevel inverters find applications in the energy sector, including cascaded H-bridge, neutral point clamped, and flying capacitor configurations [19]. In solar PV systems, a three-phase multilevel inverter is employed alongside a brushless motor and a tracking system. Pratomo *et al.* [20] developed a five-level inverter incorporating a pulse width modulated controller for flying capacitors, along with an H-bridge inverter generating five voltage levels. The use of seven-level multilevel inverters with fewer power switches, capacitors, and gates is advocated for simplifying operations, enhancing efficiency, and increasing reliability without complicating the control system [21]. In a study by Majdoul *et al.* [22], a ten-switch inverter with up to 25 voltage levels is utilized across various applications like energy, photovoltaics, power transmission, and electric vehicles. This design aims to minimize switch losses, reduce inverter size and cost, while ensuring good performance compared to other multilevel converter systems. Additionally, Majdoul *et al.* [23] employ a nine-switch inverter without clamped diodes or flying capacitors to generate different voltage levels, highlighting the superior harmonic performance of the clamped diode inverter [22], [23]. The adoption of a hybrid modulation technique is emphasized across these studies for optimal control, collectively indicating improved performance, reduced losses, and cost-effectiveness [24].

However, the control strategies discussed in the literature need an extra installations which increases the complexity and the cost of its realization. Therefore, an enhanced modulation method for three-level flying capacitor multilevel inverters (FCMLIs) is presented in this paper. Compared to the traditional methods, the enhanced modulation technique is far simpler. It combines a high-frequency square wave pulse with a sinusoidal pulse width modulation (SPWM). The two main switches (S_m) in the top and bottom of FCMLI are controlled by the square wave, which is produced at a switching frequency of 20 kHz. Positive S_p and negative S_n switches are controlled by the square wave pulse in parallel with the comparison result of the sine wave with the carrier signal (saw-tooth) and zero. This process ensures that the coupling capacitors are charged and discharged equally, resulting in the achievement of energy balancing. Furthermore, which is a key component of the flying capacitor multilevel inverters. This unquestionably contributes to maintaining the output voltage form's smoothness and stability as well as the inverter's stability and dependability. The improved modulation technique is simulated and experimentally verified.

The rest of the paper is organized as follow: the introduction to this paper is presented in section 1. Section 2 presents a discussion of the flying capacitor multilevel inverter with conventional control strategy. Section 3presents the improved control technique and its integration with the inverter. The simulation results and experimental results are presented. Finally, section 4 concludes the paper.

2. FLYING CAPACITOR MULTILEVEL INVERTER: OPERATION AND CONTROL

A FCMLI see Figure 1, is a power electronic device that enables the conversion of DC power to AC power with high voltage and low harmonic distortion. It achieves this by utilizing multiple voltage levels to generate the desired AC waveform. The FCMLI employs a series of capacitors, called flying capacitors, which are switched between different voltage levels to create the desired output waveform [25]. The conventional control strategy for FCMLIs involves the use of pulse width modulation (PWM) techniques.

PWM is a widely used control method in power electronics, which allows precise control of the output voltage or current by varying the width of the pulses in a fixed switching frequency. In the case of FCMLIs, the PWM technique is applied to control the switching of the flying capacitors [26]. The primary objective of the conventional control strategy is to maintain balanced voltages across the flying capacitors and achieve the desired output voltage waveform. This is typically done by using a reference waveform generator that produces a reference voltage waveform based on the desired output voltage. The reference waveform is compared with the actual capacitor voltages, and the resulting error signals are used to control the switching of the flying capacitors [27].

To achieve balanced capacitor voltages, a balancing algorithm is employed. The algorithm monitors the voltage levels of each flying capacitor and adjusts the switching patterns to ensure that the voltage across each capacitor remains balanced. This balancing process is crucial to ensure the efficient operation and reliability of the FCMLI [27].The conventional control strategy may include other control loops to regulate the output voltage and current, maintain the desired frequency, and protect the inverter from faults or abnormal conditions. These control loops typically involve feedback signals from sensors or measurements of the output voltage, current, and other relevant parameters.

It is worth mentioning that the conventional control strategy for FCMLIs has been extensively studied and developed over the years. Researchers in [28]–[32] have proposed various control algorithms and techniques to improve the performance, efficiency, and reliability of FCMLIs. These advancements include advanced modulation techniques, advanced control algorithms, and the integration of digital signal processors or microcontrollers for real-time control and monitoring.

The conventional control mechanism of FCML in Figure 2 is quite complicated and large as it mainly depends on the flying capacitor being balanced by a power signal, which is generated by the voltage across the capacitor and the current through the capacitor, and according to the value of the power signal the voltage state (level) are going to be chosen. The balancing of the capacitor needs an equal duration of the charging and discharging cycle, and the developed logic can be expressed mathematically by (1):

$$V_{ref} = \frac{V_{dc}}{2} \tag{1}$$

Then, the power of the flying capacitor is given by (2):

$$P_{fly} = (\frac{1}{2}V_{dc} - V_{fly}) * I_{fly} \tag{2}$$

where V_{ref} is the reference voltage of control loop, V_{dc} is the applied DC voltage, P_{fly} is the flying capacitor instantaneous power, V_{fly} and I_{fly} are voltage and current in the flying.

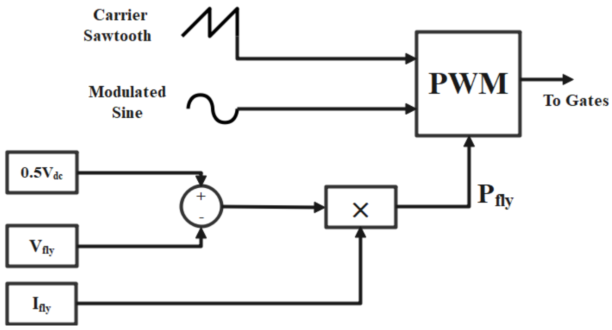

Figure 2. Conventional control loop for FCMLIs

3. THE IMPROVED MODULATION TECHNIQUE: SIMULATION AND EXPERIMENTAL

The improved control method is simulated and the results are achieved using MATLAB R2020a. The DC power supply is set to 200 V. The modulated frequency is to 50 Hz and the switching frequency is set to 20 kHz. The selected solver is ordinary differential equation ($ode23tb$) with a relative tolerance of 10 ms and a maximum step size of 0.2 ms.

3.1. Simulation results

This research paper suggests an improved method of modulation technique for 3-level flying capacitor multilevel inverter. The newly developed method is significantly simpler than conventional strategies. Four switches are utilized to control the output wave from. Two main switches are placed at the top and bottom of the inverter, named as S_m , they are controlled by an external high-frequency square wave at 20 kHz. The square wave mainly contributes to the control of the positive S_p and negative S_m switches, additionally to the comparison result of the sine wave (modulated wave) with a carrier signal (saw-tooth) and zero, according to this positive and negative levels will be produced.

This method of operation ensures that the coupling capacitors are charged and discharged in identical amounts thus achieving energy balance. Figure 3 illustrates the block diagram of the improved control algorithm. S_p operates in one-half of the cycle allowing energy transmission from the capacitor to the load producing positive output voltage at the output end, meanwhile, S_n operates in the other half of the cycle allowing energy transmission from the load to the capacitor producing negative output voltage at the output end. This process is repeated in the same way during each cycle of the input voltage. Table 1 lists all the voltage levels for each switching condition. For better illustration see Figure 4.

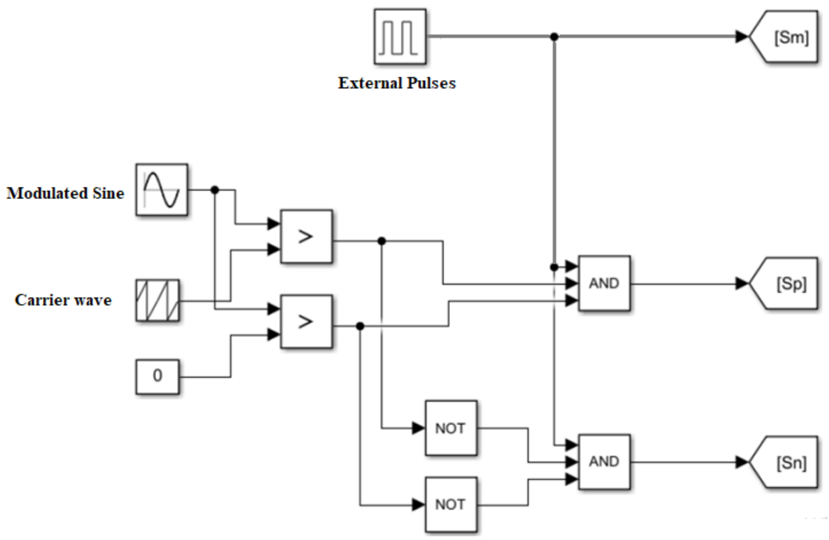

Figure 3. The improved control loop for FCMLIs

Table 1. Switches' status and load voltage

Status	S_m	S_P	S_n	V_{out}
Mode 1	ON	OFF	OFF	Zero
Mode 2	ON	ON	OFF	$0.5V_{dc}$
Mode 3	ON	OFF	ON	$-0.5V_{dc}$
Mode 4	OFF	ON or OFF	ON or OFF	Zero

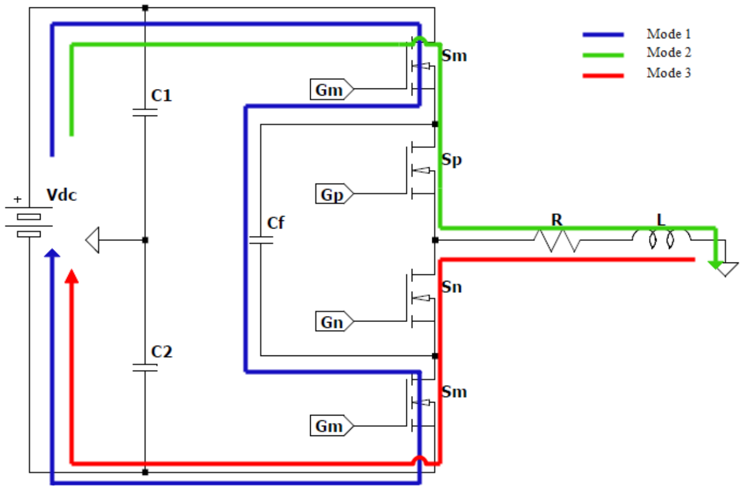

Figure 4. Modes of operation of the improved control method

According to the previous switching states in Table 1, three modes of operation are composed as follows:

- Mode 1: In the first operation mode (Zero state), the upper and lower main switches Sm are conducted, and both Sm and S_p are switched off, so,the neutral point will be connected to the load, resulting in zero output voltage across the load.
- Mode 2: In the second mode (positive state), the upper main switch S_m and the positive switch S_p are conducted. A $+Vdc/2$ voltage is produced at the load terminal by flowing through the following path: C_1-upper S_m-S_p-Load.
- Mode 3: In the third operation mode (negative state), the lower main switches are switched on, and the current will flow through the following path. C_2-lower S_m-S_n-Load, producing an output voltage of $-Vdc/2$ at the output end of the MLI.

The simulation of the the improved control technique is illustrated in Figure 5. The figure depicts that both upper and lower switches S_m are triggered on or off simultaneously. Moreover, the other two switches are gatted on or off according to the sign of the modulated sine wave. The positive switch S_P is on during positive half cycle. In contrast, the negative switch S_n is on during the negative half cycle. To show the effectiveness of the improved control technique, the single phase 3 level FCMLI is simulated using the control proposed in Figure 3. The simulated load voltage is shown in Figure 6. As expected the load voltage has three different voltage levels: 0.5 V_{dc}, $Zero$, and -0.5 V_{dc}. Lastly, to ensure the energy balance of the 3 level FCMLI controlled by the improved control technique, the voltage across both DC link capacitors are plotted in Figure 7. As seen in Figure 7, each DC link capacitor has the same DC voltage (0.5 V_{dc}) during the steady state operation of the 3 level FCLI.

3.2. Experimental results

To evaluate the efficacy of the proposed control approach, a comprehensive experimental setup was developed using the SPICE tool. Figure 8 illustrates the configuration, which incorporates two function generators. These generators produce a sinusoidal waveform with a peak to peak voltage of 5 V at a frequency of 50 Hz and a saw-tooth signal with a peak to peak voltage of 5 V at a frequency of 20 kHz. Additionally, two 12 V DC power sources are integrated into the system.

To generate pulse width modulation (PWM), the sinusoidal and the saw-tooth signals undergo a comparison process. The comparison is carried out using two LM358P operational amplifiers (OP-Amps) configured as comparators. The higher comparator generates the PWM signal, while the lower one determines the positive and negative halves of the modulated signal (representing the sign of the sine wave). Notably, during the negative half of the sinusoidal wave, the comparators remain inactive. To rectify this, a diode bridge rectifier is employed, ensuring a comprehensive evaluation of the signal. The rectified voltage is then compared with the saw-tooth signal to finalize the modulation process.

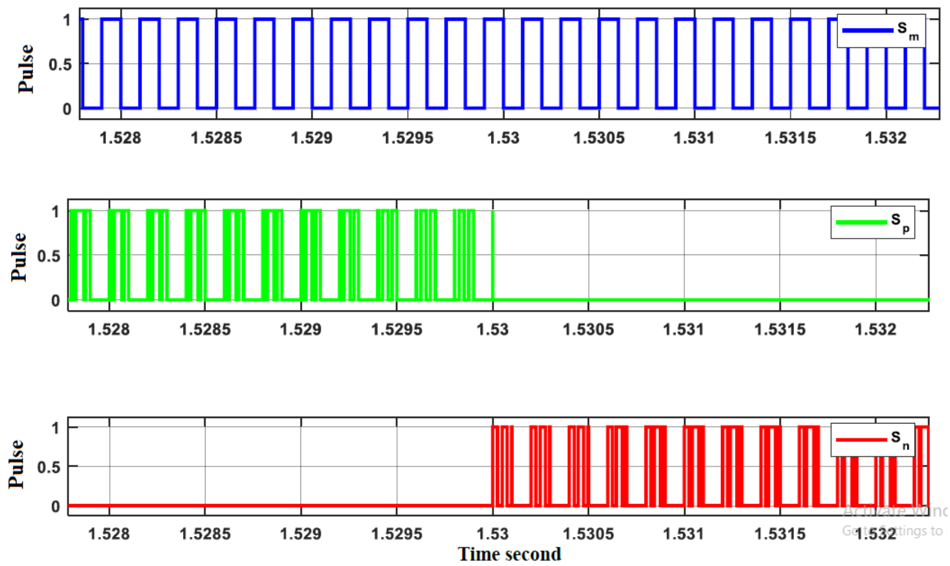

Figure 5. The output of the improved control technique

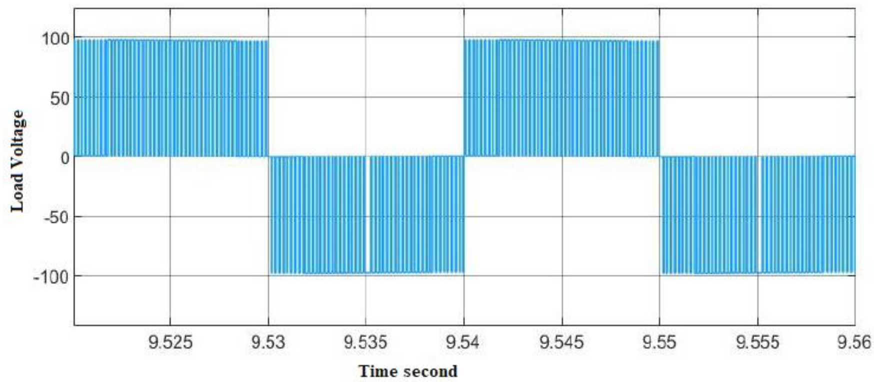

Figure 6. Load voltage of a single phase 3 level FCMLI

The LM358P operational amplifier is a widely utilized integrated circuit, serves a pivotal role in this setup. As a dual operational amplifier with low power consumption and high gain, the LM358P is adept at various signal processing tasks, including amplification, filtering, and signal conditioning. Its wide voltage operation range makes it adaptable to different power supply levels, coupled with a high input impedance and low output impedance, facilitating efficient signal transfer between stages. Moreover, the LM358P boasts a versatile input and output voltage range, rendering it suitable for both single-ended and differential signal applications. The LM358P operational amplifier continues to contribute significantly to the advancement of electronic circuits and applications, owing to its reliability, versatility, and cost- effectiveness.

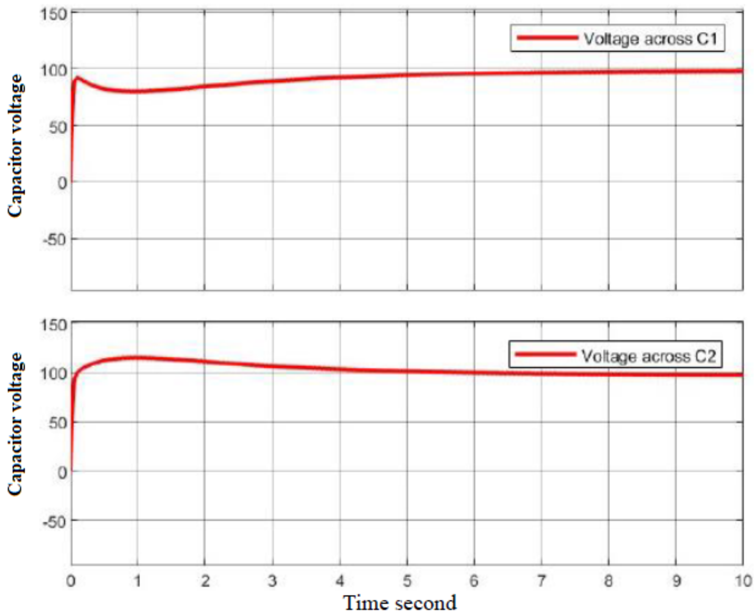

Figure 7. The average and absolute voltage across the DC link capacitors

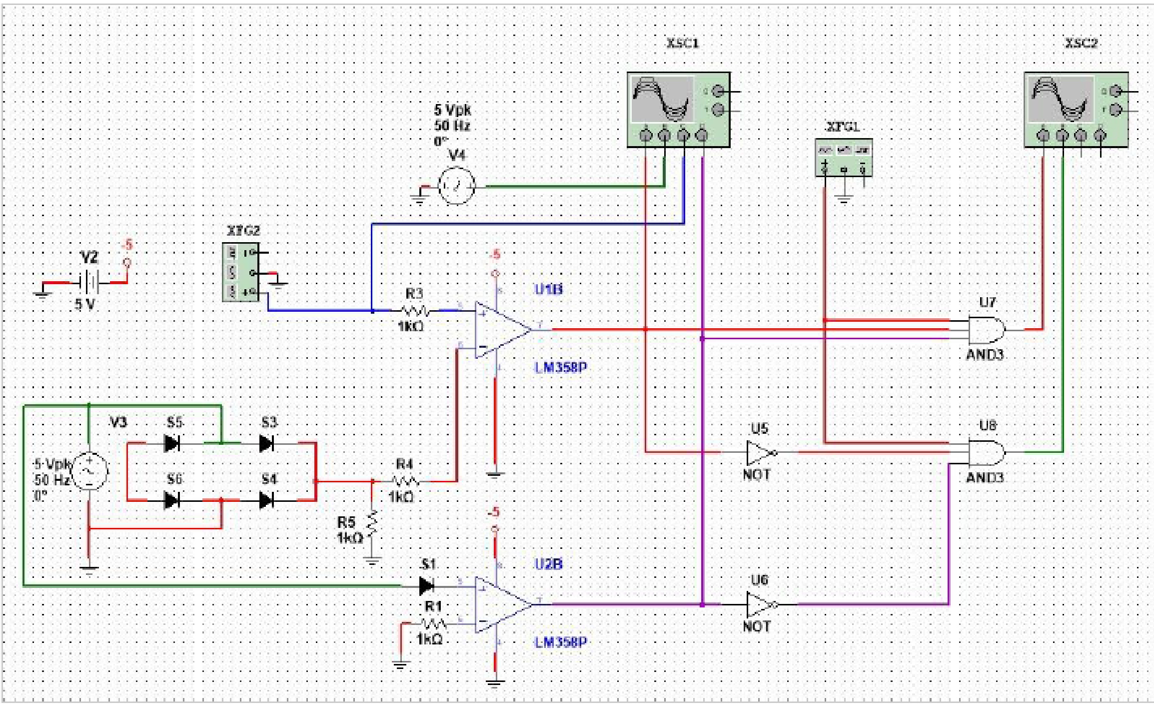

Figure 8. Test setup

Due to omitting the negative half cycle of the modulated signal, a new compensation stage has been added to the test setup. This stage uses an extra AND gate to confirm the negative sign. The modulated signal, saw-tooth, PWM and positive sign detection results are shown respectively in Figure 9. For the negative sign detection, the previous discussion would be repeated. As expected, the positive and negative switches are both gated using the pulse train shown in Figure 10. It is seen that, each switch is operated during half of sine-wave period.

As a result, the experimental section shows the simplification of applying the control loop of the proposed modulation technique. The proposed technique reduces the number of control loops from two (conventionally) to only one simple loop. The output voltage of a three-level flying capacitor multilevel inverter approves the effectiveness of applying the proposed modulation technique. Importantly, the energy balance of the coupling capacitors due to voltage balance across them is an important justification of proposing the improved modulation technique. At this stage of the research, the proposed modulation technique is only applied for the three-level FCMI and the use of this method for higher level is left for future research.

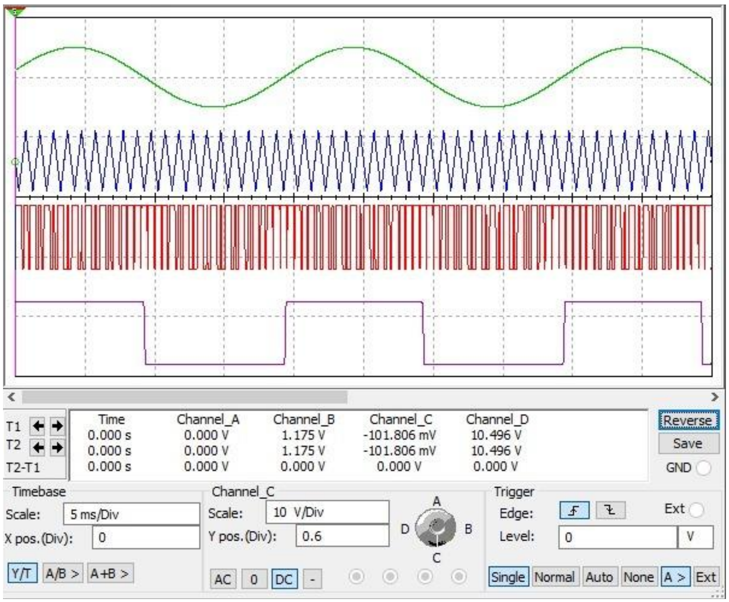

Figure 9. Waveforms: modulated wave, saw-tooth wave, PWM and positive sign detection

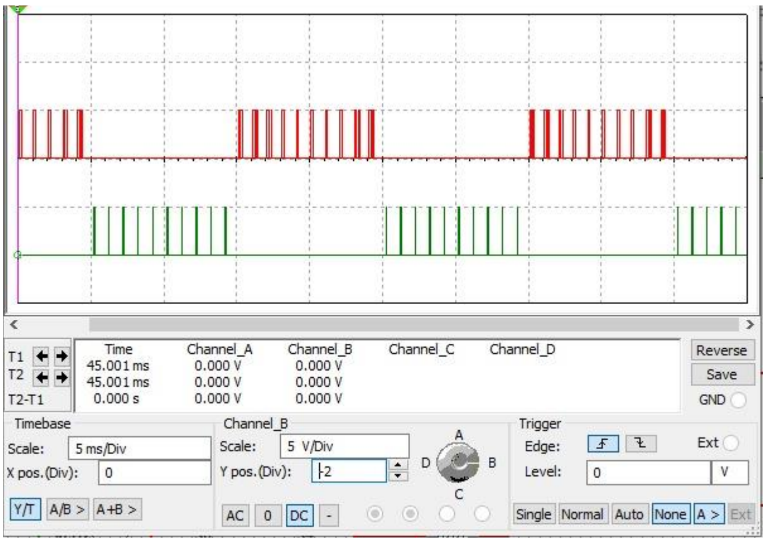

Figure 10. Waveforms: positive and negative switches' pulses

4. CONCLUSION

This paper proposed a novel efficient control modulation strategy for a three-level FCMLI. Distinguished by its user-friendly nature, this approach offers simplicity compared to traditional methods by integrating SPWM with a high-frequency square wave pulse. Operating at a frequency of 20 kHz, this square wave pulse manages both primary switches (S_m) positioned at the top and bottom of the FCMLI. The control mechanism involves the parallel utilization of the square wave pulse with the comparison outcome of the sine wave against the carrier signal (saw-tooth) and zero, governing the positive S_p and negative S_n switches. Notably, the proposed modulation technique can be implemented using logic ICs, amplifiers, and resistances, which makes it a very simple and promising technique. The technique ensures equal charging and discharging of coupling capacitors, achieving energy balance. Furthermore, the enhanced technique ensures energy balance across the flying capacitor, a pivotal component of the FCMLI, by maintaining equal charge and discharge for each capacitor during every operational cycle. This methodology simplifies control and modulation techniques, reduces component count, and mitigates challenges in maintaining voltage balance across flying capacitors. In the experimental section, the paper illustrates the simplification of the control loop in the proposed modulation technique. The method reduces the number of control loops from the customary two to a single, straightforward loop. The validation of the proposed modulation technique is demonstrated through the output voltage of the three-level flying capacitor multilevel inverter. This not only contributes to the inverter's stability and reliability but also ensures a smooth and constant output voltage. The simulation and implementation of the enhanced technique are provided and discussed in detail.

REFERENCES

[1] K. K. Gupta, A. Ranjan, P. Bhatnagar, L. K. Sahu, and S. Jain, "Multilevel inverter topologies with reduced device count: A review," *IEEE Transactions on Power Electronics*, vol. 31, no. 1, pp. 135–151, 2016, doi: 10.1109/TPEL.2015.2405012.

[2] E. Najafi and A. H. M. Yatim, "Design and implementation of a new multilevel inverter topology," *IEEE Transactions on Industrial Electronics*, vol. 59, no. 11, pp. 4148–4154, 2012, doi: 10.1109/TIE.2011.2176691.

[3] A. Ahmad and S. Maqbool, "Square wave inverters–a performance comparison with pure sine wave inverters," *International Journal Of Research in Electronics and Computer Engineering*, vol. 7, no. 1, pp. 237–239, 2019.

[4] T. Qanbari and B. Tousi, "Single-source three-phase multilevel inverter assembled by three-phase two-level inverter and two single-phase cascaded H-Bridge inverters," *IEEE Transactions on Power Electronics*, vol. 36, no. 5, pp. 5204–5212, 2021, doi: 10.1109/TPEL.2020.3029870.

[5] I. A. Altawil, K. A. Mahafzah, and A. A. Smadi, "Hybrid active power filter based on diode clamped inverter and hysteresis band current controller," in *2012 2nd International Conference on Advances in Computational Tools for Engineering Applications*, 2012, pp. 198–203, doi: 10.1109/ICTEA.2012.6462865.

[6] L. Franquelo, J. Rodriguez, J. Leon, S. Kouro, R. Portillo, and M. Prats, "The age of multilevel converters arrives," *IEEE Industrial Electronics Magazine*, vol. 2, no. 2, pp. 28–39, Jun. 2008, doi: 10.1109/MIE.2008.923519.

[7] A. Akbari, J. Ebrahimi, Y. Jafarian, and A. Bakhshai, "A multilevel inverter topology with an improved reliability and a reduced number of components," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 10, no. 1, pp. 553–563, Feb. 2022, doi: 10.1109/JESTPE.2021.3089867.

[8] M. Malinowski, K. Gopakumar, J. Rodriguez, and M. A. Perez, "A survey on cascaded multilevel inverters," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 7, pp. 2197–2206, 2010, doi: 10.1109/TIE.2009.2030767.

[9] P. N. Rao and L. M. Saini, "Photovoltaic-based grid-connected transformer-less three-phase cascaded diode-clamped multilevel inverter with reduced leakage current," *International Journal of Circuit Theory and Applications*, vol. 50, no. 7, pp. 2398–2422, 2022, doi: 10.1002/cta.3257.

[10] M. T. Fard, W. A. Khan, J. He, N. Weise, and M. Abarzadeh, "Fast online diagnosis of open-circuit switching faults in flying capacitor multilevel inverters," *Chinese Journal of Electrical Engineering*, vol. 6, no. 4, pp. 53–62, Dec. 2020, doi: 10.23919/CJEE.2020.000030.

[11] M. A. Memon, M. D. Siddique, S. Mekhilef, and M. Mubin, "Asynchronous particle swarm optimization-genetic algorithm (APSO-GA) based selective harmonic elimination in a cascaded H-Bridge multilevel inverter," *IEEE Transactions on Industrial Electronics*, vol. 69, no. 2, pp. 1477–1487, Feb. 2022, doi: 10.1109/TIE.2021.3060645.

[12] X. Jiang and M. L. Doumbia, "Comparative study of grid-connected multilevel inverters for high power phtovoltaic systems," in *Proceedings of 2019 the 7th International Conference on Smart Energy Grid Engineering*, 2019, pp. 184–190, doi: 10.1109/SEGE.2019.8859784.

[13] G. Kampitsis, E. I. Batzelis, A. Kolokasis, E. Matioli, and B. C. Pal, "A generalized phase-shift PWM extension for improved natural and active balancing of flying capacitor multilevel inverters," *IEEE Open Journal of Power Electronics*, vol. 3, pp. 621–634, 2022, doi: 10.1109/OJPEL.2022.3209540.

[14] K. R. Sreejyothi, K. Chenchireddy, N. Lavanya, R. M. Reddy, K. Y. G. Prasad, and R. Revanth, "Level-shifted PWM techniques applied to flying capacitor multilevel inverter," in *Proceedings of the International Conference on Electronics and Renewable Systems*, 2022, pp. 41–46, 2022, doi: 10.1109/ICEARS53579.2022.9752074.

[15] Z. Song, W. Chen, and C. Xia, "Predictive direct power control for three-phase grid-connected converters without sector information and voltage vector selection," *IEEE Transactions on Power Electronics*, vol. 29, no. 10, pp. 5518–5531, 2014, doi: 10.1109/TPEL.2013.2289982.

[16] A. Bakeer, I. S. Mohamed, P. B. Malidarreh, I. Hattabi, and L. Liu, "An artificial neural network-based model predictive control for three-phase flying capacitor multilevel inverter," *IEEE Access*, vol. 10, pp. 70305–70316, 2022, doi: 10.1109/ACCESS.2022.3187996.

[17] H. Wang, X. Chen, Y. Liu, M. Su, W. Feng, and W. Yu, "Model predictive control of three-phase voltage-source converters with improved tracking performance," *ISA Transactions*, vol. 133, pp. 424–434, 2023, doi: 10.1016/j.isatra.2022.07.012.

[18] M. Bouzidi, S. Barkat, A. Krama, and H. Abu-Rub, "Generalized predictive direct power control with constant switching frequency for multilevel four-leg grid connected converter," *IEEE Transactions on Power Electronics*, vol. 37, no. 6, pp. 6625–6636, 2022, doi: 10.1109/TPEL.2022.3142113.

[19] M. T. Yaqoob, M. K. Rahmat, S. M. M. Maharum, and M. M. Su'ud, "A review on harmonics elimination in real time for cascaded h-bridge multilevel inverter using particle swarm optimization," *International Journal of Power Electronics and Drive Systems*, vol. 12, no. 1, pp. 228–240, 2021, doi: 10.11591/ijpeds.v12.i1.pp228-240.

[20] L. H. Pratomo and S. Riyadi, "Design and implementation of a single-phase five-level inverter using a dc source with voltage balancer on capacitor," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 12, no. 2, pp. 902–912, 2021, doi: 10.11591/ijpeds.v12.i2.pp902-912.

[21] R. A. Ahmed, E. D. Hassan, and A. H. Saleh, "A new flying capacitor multilevel converter topology with reduction of power electronic components," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 14, no. 2, pp. 1011–1023, 2023, doi: 10.11591/ijpeds.v14.i2.pp1011-1023.

[22] R. Majdoul, A. Touati, A. Ouchatti, A. Taouni, and E. Abdelmounim, "Improved 25-level inverter topology with reduced part count for PV grid-tie applications," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 12, no. 3, pp. 1687–1698, 2021, doi: 10.11591/ijpeds.v12.i3.pp1687-1698.

[23] R. Majdoul, A. Touati, A. Ouchatti, A. Taouni, and E. Abdelmounim, "A nine-switch nine-level converter new topology with optimal modulation control," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 12, no. 2, pp. 932–942, 2021, doi: 10.11591/ijpeds.v12.i2.pp932-942.

[24] A. A. Abbood, "Harmonic spectra of BLDC motor supplied by a solar PV," *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 20, no. 3, pp. 1693–1702, 2020, doi: 10.11591/ijeecs.v20.i3.pp1693-1702.

[25] A. V. Singh and R. S. Singh, "A comparative study of multilevel inverter topologies," *International Research Journal of Engineering and Technology*, vol. 9001, 2008.

[26] A. Namboodiri and H. Wani, "Unipolar and bipolar PWM Inverter," *International Journal for Innovative Research in Science and Technology*, vol. 1, no. 7, 2014.

[27] B. S. Jin, W. K. Lee, T. J. Kim, D. W. Kang, and D. S. Hyun, "A study on the multi-carrier PWM methods for voltage balancing of flying capacitor in the flying capacitor multi-level inverter," *IECON Proceedings (Industrial Electronics Conference)*, vol. 2005, pp. 721–726, 2005, doi: 10.1109/IECON.2005.1568993.

[28] S.-G. Lee, D.-W. Kang, Y.-H. Lee, and D.-S. Hyun, "The carrier-based PWM method for voltage balance of flying capacitor multilevel inverter," in *2001 IEEE 32nd Annual Power Electronics Specialists Conference (IEEE Cat. No.01CH37230)*, 2001, vol. 1, pp. 126–131, doi: 10.1109/PESC.2001.954006.

[29] M. Sarbanzadeh, M. A. Hosseinzadeh, E. Sarebanzadeh, and M. Rivera, "Recent predictive control strategies applied to flying capacitor multilevel inverters," *IEEE ICA-ACCA 2018 - IEEE International Conference on Automation/23rd Congress of the Chilean Association of Automatic Control: Towards an Industry 4.0*, 2018, doi: 10.1109/ICA-ACCA.2018.8609794.

[30] A. Khoshkbar-Sadigh, V. Dargahi, and K. Corzine, "New flying-capacitor-based multilevel converter with optimized number of switches and capacitors for renewable energy integration," *IEEE Transactions on Energy Conversion*, vol. 31, no. 3, pp. 846–859, 2016, doi: 10.1109/TEC.2015.2508481.

[31] L. Zhang, S. Watkins, and D. Chang, "Control of multilevel flying capacitor inverters for high performance," in *2006 5th International Power Electronics and Motion Control Conference*, Aug. 2006, vol. 3, pp. 1–6, doi: 10.1109/IPEMC.2006.297337.

[32] A. Redouane, R. Saou, and A. Oukaour, "Flying capacitor voltage balancing control strategy based on logic-equations in five level ANPC inverter," *Periodica Polytechnica Electrical Engineering and Computer Science*, vol. 67, no. 4, pp. 438–448, 2023, doi: 10.3311/PPee.21879.

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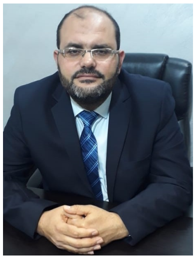

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