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Comparison and Analysis of Three-Phase Three-Level T type and F-Type Multilevel Inverters

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Abstract Multilevel inverters (MLIs) are widely used in high-power applications due to their superior efficiency, lower total harmonic distortion (THD), and improved power quality. These inverters generate a near-sinusoidal waveform, making them preferable to two-level (2L) inverters in applications such as industrial drives, renewable energy systems, and high-voltage direct current (HVDC) transmission. While 2L inverters are commonly used in low and medium-power applications due to their simple modulation technique and fewer switches, they face limitations in high-power scenarios. Specifically, 2L inverters struggle with switch stress, increased filter requirements, and electromagnetic interference (EMI) issues. To address these challenges, this paper introduces a three-phase three-level F-type and T-type inverter topology. This proposed design reduces switching and conduction losses while maintaining better efficiency than traditional 2L inverters. The innovative topological structure of the proposed inverter enhances its overall performance, making it a more efficient solution for high-power applications. Simulation results validate the effectiveness of the proposed three-level F-type inverter, demonstrating its improved efficiency and reduced power losses. This advancement in MLI technology offers a promising alternative to conventional inverters, ensuring higher reliability and better operational performance in demanding industrial applications.

Keywords —F-Type Multilevel inverter, T-Type Multilevel Inverter, Sinusoidal Pulse Width Modulation (SPWM), Efficiency, Switching Losses, Conduction Losses, Grid.

I. INTRODUCTION

Three-phase rectifiers are commonly employed in high-power applications, including industrial motor drives, power supplies, renewable energy systems, and electric vehicle (EV) charging stations. Unlike single-phase rectifiers, they offer higher power handling capability, lower harmonic distortion, and enhanced efficiency [1]. By integrating multilevel topologies, three-phase rectifiers provide several benefits, including:

- Enhanced power quality: Lower total harmonic distortion (THD) and improved waveform quality.
- Smaller passive filters: Decreases the size, cost, and weight of filtering components.
- Reduced voltage stress on semiconductors: Enhances system reliability and efficiency.
- Lower common-mode voltage: Minimizes electromagnetic interference (EMI).
- Higher conversion efficiency: Reduces switching and conduction losses.

Multilevel inverters (MLIs) are advanced power electronic converters that generate high-quality AC output by utilizing multiple DC voltage levels. They are widely employed in medium- and high-power applications such as renewable energy systems, industrial motor drives, electric vehicles (EVs), and grid-connected systems [2]-[5]. Their ability to provide higher efficiency, lower harmonic distortion, and reduced voltage stress on switching devices makes them a crucial component in modern power electronics.

MLIs play a key role in grid-connected applications, ensuring reliable and efficient power conversion. Among various MLI topologies, Neutral-Point Clamped (NPC), T-

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Type NPC, and F-Type MLIs are commonly used due to their cost-effectiveness, improved efficiency, and reliability. With the growing demand for renewable energy and smart grid technologies, MLIs will continue to be a vital solution for enhancing power quality and system performance [6]-[7].

A three-phase two-level (2L) inverter has several disadvantages compared to a three-level (3L) inverter, particularly in high-power applications. One major drawback is its higher total harmonic distortion (THD), which results in a more distorted output waveform, requiring larger and more expensive filters to improve power quality [8]. Additionally, switching losses are higher in 2L inverters due to larger voltage steps (dv/dt), which not only increases power dissipation but also leads to greater electromagnetic interference (EMI), requiring additional filtering and shielding. Another key disadvantage is the higher voltage stress on semiconductors in 2L inverters, as the power switches must withstand the full DC bus voltage, potentially reducing their lifespan and reliability. In contrast, 3L inverters distribute voltage across multiple switches, minimizing stress and improving durability. Furthermore, larger filter requirements in 2L inverters contribute to increased system size, cost, and weight. Finally, efficiency in high-power applications is lower, as 2L inverters suffer from higher conduction and switching losses compared to 3L inverters, which optimize power distribution and reduce losses[9]-[10]. Due to these limitations, three-level inverters are preferred in applications requiring high efficiency, lower harmonic distortion, and reduced voltage stress, such as industrial motor drives, HVDC systems, and renewable energy integration [11]-[12].

SiC MOSFETs offer low on-resistance, low switching losses, high-temperature operation, and high-withstanding capability. This enables miniaturization of cooling and passive components in power electronics equipment. To fully utilize SiC MOSFETs' potential, both device and packaging technologies are crucial. Advanced packaging solutions are necessary to achieve high-power density, compact designs, and improved reliability and thermal performance. This synergy will expand SiC MOSFET applications, driving innovation in power electronics [13].Silicon Carbide (SiC) is a promising semiconductor material with a wider bandgap than silicon, offering superior electrical performance. SiC MOSFETs have gained attention due to their low switching loss and high operating frequency. However, high-voltage SiC MOSFETs face challenges, particularly in reducing device size and drift region resistance. The super junction (SJ) structure has been a breakthrough in power devices, achieving a better trade-off between breakdown voltage and on-resistance by introducing a transverse electric field to the drift layer, paving the way for further advancements in SiC MOSFET technology [14]. The body effect in SiC MOSFETs decreases the threshold voltage. Two primary causes of Bias Temperature Instability (BTI) characteristics are: (1) small energy band offset at the SiC/SiO2 interface, and (2) numerous charge traps at the SiC/SiO2 interface, affecting device reliability [15]. Silicon carbide (SiC) has emerged as a promising material in the field of power electronics, offering numerous advantages over traditional silicon-based devices. These benefits include:1. Low Switching Loss: SiC devices exhibit significantly reduced switching losses, enabling higher-frequency operation and improved overall efficiency.2. Low Conduction Resistance: SiC devices have lower conduction resistance, resulting in reduced energy losses and increased power handling capability.3. High-Temperature Stability: SiC devices demonstrate stable operating characteristics at elevated temperatures, making them ideal for high-power and high-temperature applications [16].SiC devices offer superior efficiency, faster switching speeds, and robust operation, especially at high temperatures. Their ability to operate at higher voltages than silicon counterparts makes them ideal for high power density and efficiency applications. SiC semiconductors are poised to play a critical role in enabling this transformation as the world transitions to a more sustainable future [17]. A comprehensive cost comparison between Silicon (Si) IGBTs and Silicon Carbide (SiC) MOSFETs was conducted for a Modular Multilevel Converter (MMC) based delta STATCOM. SiC MOSFETs offer advantages due to their low conduction and switching losses compared to Si IGBTs. The extra investment in SiC MOSFETs can be recovered in as little as two years, depending on the scenario. This finding is significant for industrial applications and researchers, highlighting the potential of SiC MOSFETs in high-power electronics [18].

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Limitations of 2-Level VSI in Industrial Applications

Higher conduction and switching losses compared to 3-level inverters. At higher fundamental frequencies (above 1 kHz), losses become significant. This leads to increased heat generation, requiring larger heatsinks and cooling. In high-power motor drives, 2L inverters commutate large currents at high switching frequencies, causing: Increased voltage stress on the switches and higher dv/dt, leading to motor insulation stress bearing currents, and Electro Magnetic Interference (EMI) issues. The fast switching of IGBTs leads to high-frequency ripple currents at the DC link, Oversized DC capacitors are needed to handle the ripple, increasing system cost and size, this issue is more critical in high-power applications (>100 kW) [8].

This paper discusses the T-Type and F-Type 3-Level Inverters, comparing their performance against a 2-Level inverter. A detailed analysis is conducted to evaluate their efficiency, voltage stress, switching losses, and overall advantages, highlighting the benefits of multilevel topologies in high-power applications.

II. PULSE WIDTH MODULATION (PWM)

Sinusoidal pulse width modulation is one of the many pulse width modulation methods, which is also simplest and widely used. Basically in sinusoidal pulse width modulation technique, a reference signal for each phase is generated and compared with a triangle signal, whose frequency is set to switching frequency. Switches are turned on when the reference signal becomes higher than triangular waveform and turned off when the reference signal becomes lower than triangular waveform. According to the frequency of triangular waveform, switching frequency of inverter is defined. Each reference waveform has a phase difference of 120° between one and another, as shown in illustration of sinusoidal pulse width modulation technique below Figure 1. According to the frequency of triangular waveform, high frequency switching harmonic occurs at the line currents.

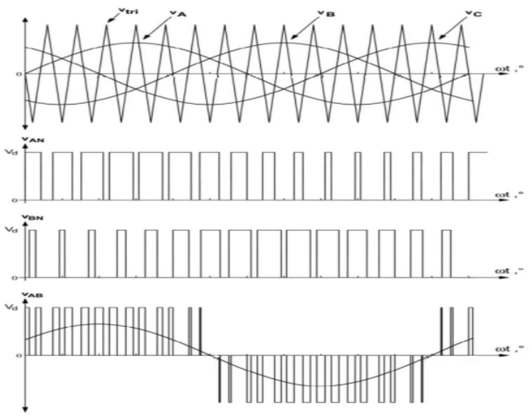

Figure 1. Illustration of sinusoidal pulse width modulation technique

III. MATHEMATICAL MODEL ANALYSIS THREE-PHASE TWO-LEVEL

A mathematical analysis is discussed in this section. First, the switching and conduction losses are calculated for 2-level and 3-level three-phase inverters. Second, the efficiency of three-phase 3-level inverters is calculated. Various case studies are considered for the analysis of these inverters.

Case Studies

1. Conduction Losses: Conduction loss occurs when the IGBT is in its "on" state and allows current to flow. This loss depends on following conditions. Equations 1 and 2 are the conduction loss for IGBT and Diode.

1) the on-state voltage and the current flowing through the device.

2) The conduction loss Pcond, IGBT for an IGBT is calculated as:

$$P_{cond}\ (IGBT) = V_{ceo} * i_{avg} + R_0 * i^2 \qquad (1)$$

$$P_{cond}\ (Diode) = V_{d0} * i_{avg} + R_{d0} * i^2 \qquad (2)$$

Where, P_{cond} is conduction loss in IGBT, V_{CE0} is collector-emitter saturation voltage of the IGBT, I_{avg} is average load current flowing through the IGBT, I is current through diode, and R0 is On-state resistance. It is given as

$$R0 = (V_{ce2} - V_{ce1}) / (I_{c2} - I_{c1}) \qquad (3)$$

Where Vce1, and Vce2 are collect-emitter saturation voltages at different conditions. I_{c1} and I_{c2} are current through the collector.

2. Switching Losses: Switching loss occurs when the IGBT transitions between its "on" and "off" states.

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During these transitions, the overlap of voltage and current causes energy dissipation. The switching loss P_{sw}, IGBT per cycle is given by

$$Psw(IGBT) = f \times (Eon + Eoff) \quad (4)$$

Where P_{sw} is switching loss in IGBT, f is the switching frequency, Eon & Eoff are the energy losses during turn-on and turn-off transitions, respectively.

$$P_{DIODE} = (E_{REC}) * F_{SW} \quad (5)$$

$$= (E_{ON} + E_{OFF}) * \frac{F_{SW}}{\pi} * \frac{I_{pk}}{I_{nom}} * \frac{V_{dc\,link}}{V_{nom}}$$

Where, F_{sw} = Switching Frequency

I_{pk} = Peak Collector Current

I_{nom} = Nominal Rated current of Device

$V_{dc\ link}$ = DC Link Voltage

V_{nom} = Datasheet Dynamic V line

E_{on} = Turn on Energy Losses

E_{off} = Turn off Energy Losses

E_{rec} = Diode Reverse Recovery Energy Loss

Output Power is given as $S=\sqrt{3}\, V_L\, I_L$

S= apparent power (kv) is taken as 10KVA in this paper.

Peak Grid Voltage is given as **338.8V** (415 sqrt 2/3)

Therefore, 10 KVA=$\sqrt{3}$*415 I_L

$$I_L = \frac{10000}{\sqrt{3} * 415} = \frac{10000}{1.732 * 415} = \frac{10000}{718.78} = \mathbf{13.912\ A}$$

$$I_L = I_M * \text{sqrt } 2 = 19.61\text{ A}$$

Where Peak value of grid current is **19.6 A**

Then, RMS Value I_{rms} = 19.6/$\sqrt{2}$ =**13.8613 A**

3. Efficiency for Si IGBT

η= Output Power/Output Power +Losses

=1.732∗415∗13.8613/1.732∗415∗13.8613+63.0047

= **99.37 %**

SiC MOSFET

η= Output Power/Output Power +Losses =

=1.732∗415∗13.8613/1.732∗415∗13.8613+21.3241

= 99.78 %

The efficiency values are based on simulations and may vary depending on the specific application and implementation.In the table I comparison of the efficiency of three-phase two level,three-phase three-level T-type and F-type grid connected inverters.

Table I Comparison of efficiency

S.no		Si IGBT	SiC MOSFET
1	3-2L Inverter	99.37 %	99.78 %
2	3-3L T-Type Inverter	99.65 %	99.82 %
3	3-3L T-Type Inverter	99.63%	99.77 %

IV. RESULTS AND DISCUSSIONS

Figure 2 illustrates the three-phase, three-level T-type multilevel inverter, while Figure 3 presents the three-phase, three-level F-type inverter. The result analysis is conducted using PLECS software. The parameters of both inverters are detailed in Table II, providing a basis for performance evaluation and comparison between the two inverter topologies.

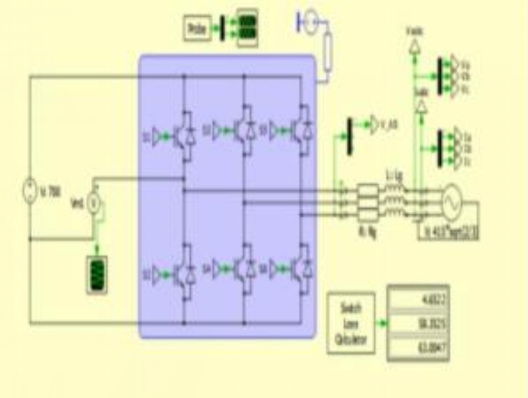

Figure 2. Simulation Diagram of 3-phase 3-level T-type inverter

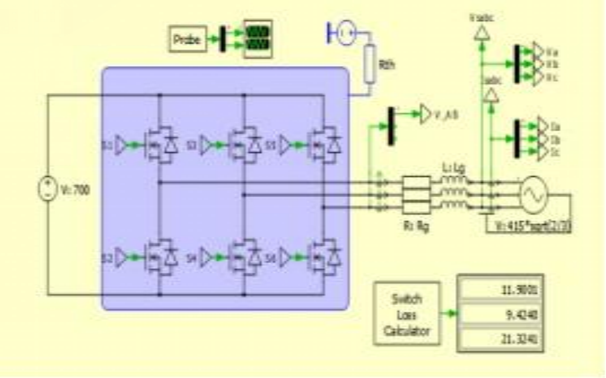

Figure 3. Simulation Diagram of 3-phase 3-level F- type inverter

Figure 4 depicts the output voltage and current response of a 3-phase, 3-level T-type inverter operating at unity power factor. Similarly, Figure 5 illustrates the output voltage and current response of a 3-phase, 3-level F-type inverter, also

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maintaining unity power factor, enabling a comparative performance analysis between both topologies.

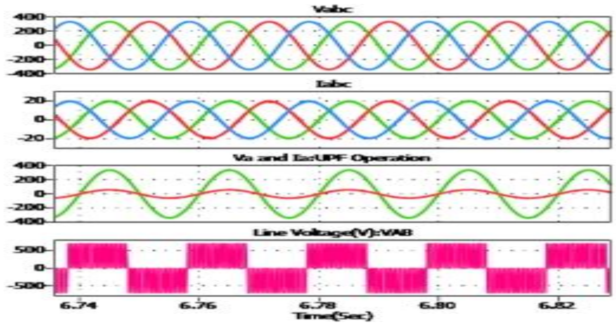

Figure 4. output response of 3-phase 3-level T-type inverter

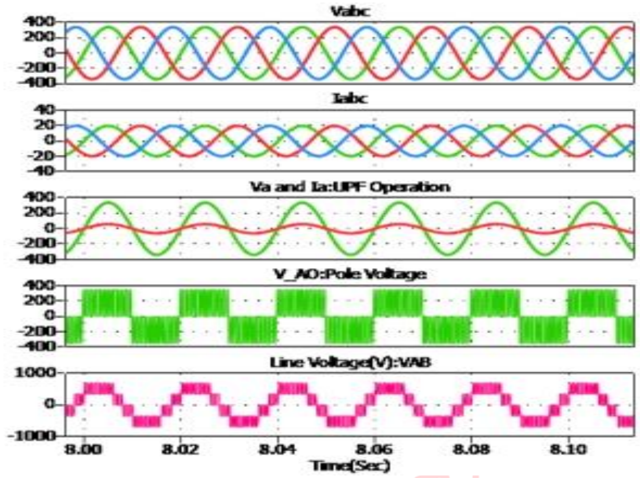

Figure 5 output r**esponse of 3-phase 3-level F-type inverter**

The benefits of 3-Level NPC and 3-Level T-NPC inverters are Improved efficiency, reduced THD, increased power density, and cost-effectiveness with better reliability and grid compatibility. Enhanced thermal performance, reduced switching losses, and smaller filter sizes also contribute to their benefits in various applications.

Table II. Benefits of 3-Level NPC and 3-Level T-NPC Inverters

S.No	Feature	2L NPC VSI	3L NPC VSI	3L T NPC VSI
1	Number of Voltage Levels	2 (+Vdc, -Vdc)	3 (+Vdc/2, 0, -Vdc/2)	3 (+Vdc/2, 0, -Vdc/2)
2	Switching Losses	High	Lower than 2L VSI	Lower than NPC(due to fewer conduction paths)
3	Conduction Losses	High	Lower	Lower than NPC
4	Voltage Stress on Switches	Vdc per switch	Vdc/2 per switch (reducing dv/dt stress)	Vdc/2 per switch
5	Total Harmonic Distortion (THD)	High	Lower THD (better waveform quality)	Lower than NPC
6	Motor Insulation Stress	High (due to large dv/dt	Lower	Lower than NPC
7	System Cost	Large (due to ripple currents)	Reduced capacitor size	Reduced capacitor size
8	Efficiency	94-96%	96-98%	98-99%

Table 3.System parameters

S.No	Parameter	Value
1	SiC MOSFET module	UJ4C075018K4S
2	IGBT Module with diode module	DIM900MIHS 12-PG500
3	Grid voltage	415 V
4	Frequency	10 kHZ
5	Resistance	0.01 Ohm
6	Inductance	4 m H
7	DC Link voltage	700 V

V. CONCLUSION

Multilevel inverters (MLIs) are widely used in high-power applications due to their superior efficiency, lower total harmonic distortion (THD), and improved power quality. These inverters generate a near-sinusoidal waveform, making them preferable to two-level (2L) inverters in applications such as industrial drives, renewable energy systems, and high-voltage direct current (HVDC) transmission. This proposed design reduces switching and conduction losses while maintaining better efficiency than traditional 2L inverters. The innovative topological structure of the proposed inverter enhances its overall performance, making it a more efficient solution for high-power applications. Simulation results validate the effectiveness of the proposed three-level F-type and T-type inverters, with improved efficiency and reduced power losses.

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