DESIGN REVIEW 4

Grid Connected T-Type Converter

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Client:

Dr. Venkata Yaramasu

Date:

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Introduction

This project is about the Grid connected T-Type Converter that will greatly compliment the recent energy developments of the Solar PV energy. The converter will help to efficiently transform the solar energy for usage. The project offers the following advantages; three-level output waveform, balanced DC capacitor voltage, small harmonic filter, fast switching and low electromagnetic interference. This design will be implemented using Matlab-Simulink and dSPACE. The neutral-point clamped (NPC) converter used in the high-power industrial applications produces uneven heat dissipation and switching losses between the inner and outer IGBTs leading to difficulties in the thermal design of converter. The T-type converter with bidirectional switches solves the issues of NPC converter while preserving best qualities such as three-level output waveform, balanced DC capacitors voltage during all operating conditions, lower size of output harmonic filter, increased equivalent switching frequency, and lower electromagnetic interference.

T type converters come as an alternative on low voltages because of its low conducting losses and its simplicity on isolated gates controls. In addition, they are the best alternatives in industries due to its performance since it combines the advantages of 2 level and 3 level converters. The T type inverter topology series connection of lower and upper switches allows it to operate on high frequencies and high-speed variable systems. Besides, it is better than the other three-level inverters when using in low voltage system. Instead of 3 level NPC topology, a bidirectional switch is connected to DC link midpoint making an alternative reliable 3 level topology. The bidirectional switches of T type inverter block half of DC ink voltage only hence its acceptable conduction losses. Thus, a successful design, simulations, and implementation of the three-phase grid-connected T-type converter will provide a new dimension in the grid connection and energy industry as a whole.

The group members for this project who have varied roles and contributions are, Jafar Ahmad, Abdullah Alotaibi and Saad Alqahtani. Jafar is responsible for development of simulation codes and models while Abdullah carried documentation, research on components needed and interfacing all power points. Saad dealt with wiring of the circuitry and ensured no loose connections and correct voltages. We had planned to do simulations on Matlab & dSPACE before we perform the real fabrication of the circuits on a PCB.

Our clients is Dr. Venkata Yaramasu who has extensive experience in renewable energy, model predictive control, smart grid systems, and other areas of the energy field. With this valuable experience, we find it instrumental in our capstone project. We as the JAS TtC are glad to work on the T-type converter as it will eliminate the challenges being faced with the neutral-point clamped converter. Here is powerful system that has three-level output waveform, balanced DC capacitors voltage during all operating conditions, lower size of output harmonic filter and increased equivalent switching frequency. Some of its special features are;

- Three-level output waveform.
- Balanced DC capacitor voltage.
- Small harmonic filter.
- Fast switching.
- Low electromagnetic interference

Literature Review **(Abdullah)**

A T-Type converter is a multilevel bidirectional switching type mechanism converter that replaces the NPC converter. Its bidirectional involve DC link connection neutral to the midpoint because of this it has fewer diodes comparing with NPC and contains the equal number of IGBT switches. To design the bidirectional switches, there are different ways available; as one of them is reverse blocking the IGBT switches, another way is to develop two conventional IGBT switches in reverse directions. The second method is considering to be more reliable because of the low switching losses. As part of the literature review, a discussion of prior art and standards regarding the T-type converter is presented below.

Single stage configuration

Sachin's et al. work [1] has provided an introduction into how the T-Type inverter topology was made as the same is also part of a single-stage topology. From this topology, we can learn the Pulse Width Modulation control strategy and how it works well with Maximum Power Point Tracking of the solar PV systems [1]. To fully understand the structural features of the T-Type converter, Jacek's and Rafal's [2] research article provides an insight into how T-type converter can be used in combination with other topologies to realize a more enhanced performance. For this, the extended version of the T-Type converter, which combines a three-phase inverter with a three-level DC-DC converter, and a comparison, is also made a combination of the T-type inverter with a boost converter [2]. There has been a concern on how the neutral point of the multilevel inverters can be controlled, and to help in knowing how to manage the same, Zorig et al. [3] article shares insight into how the three-level inverter for solar system can be controlled.

Pulse Width Modulation control

In Sachin et al. work [1], a description of how the PWM can be used in combination with the Maximum Power Point Tracking control strategy has been discussed in depth. The structure used here has a high power handling capability due to division of the handling capacity of the configuration into two voltage half-cycles. The drawbacks of using two boost converters to compliment the T-type converter have been blamed on the hard switching of the devices at high frequencies thus making it not suitable for grid-tied systems. This article [1]is critical in finding the best topology to use in combination with the three-level T-type converter. The other combination that has been discussed by Sachin et al. is the one that uses a half-bridge buck-boost converter to eliminate the need to symmetrically switch on during operation of the two voltage half-cycles. This means that there is no hard switching requirement and losses arising from the same. However, Sachin says that such a configuration requires high-value filter capacitors for each of the PV sources [1].

Multilevel inverter topology

Though the multilevel inverter topology has enhanced performance, the primary concern has been on the neutral point voltage level that is ever-shifting. Zorig [3] proposes a method to control this neutral point voltage by suggesting a two-stage conversion that uses a three-level DC-DC boost converter in combination with a three-level converter. The structural featured include the usage of two split DC capacitors on the side of the boost converter, thus eliminating the need to change the ordinary algorithm of three-level space vector modulation (SVPWM) or making additional structural change [3]. There is only one Proportional-Integral (PI) required to achieve a proper neutral point voltage balance. The combination of these two can also control the amount of current injected into the grid and obtain appropriate reactive power compensation. The future works and also of the considerations that I have gained from this article is the need to investigate more on the neutral point voltage at various conditions.

Three-stage three-level T-type neutral point

In Altin et al. work [4] , a three-stage three-level T-type neutral point clasped network connected inverter with a decreased number of the switch has been proposed for distributed generation systems. The proposed inverter topology has just two legs and of eight semiconductor switches. Thus, advantageous multi-level inverter technology has been accomplished with less number of semiconductor switches resulting in diminished circuit complexity. The proportional-resonant controller in stationary reference casing is intended to control the proposed inverter, thus fast powerful reaction and great reference tracking ability are obtained with zero steady-state mistakes. The feasibility and correct operation of the proposed system is validated through MATLAB/Simulink simulation studies. The obtained results show that the proposed three-stage three-level T-type inverter exhibits practically identical execution with the conventional T-type inverters. Furthermore, the total symphonious distortion level of the output current is computed as 2.07%, which is as per the limits determined by the international standards, for example, IEC61727 and IEEE1547 [4]

Extended T-Type inverter

The Jacek et al. [2] extended T-Type inverter further compliments Sachin's [1]work on how to achieve enhanced performance through a combination of the three-level T type inverter with a three-level DC-DC converter. The combination of those two shown improved performance compared to the single-level T-type inverter and single-level boost converter. The input voltage is substantially boosted by this configuration, but the only challenge was on the unstable neutral point voltage. The required DC link capacitors and the connected inductor at the input are significantly reduced. What interested me much about this article is the fact that simulations have been done, and related results are shown to show power losses. The low capacitance used in the circuit still managed to balance the neutral point voltage and the efficiency of the same is very high. The simulation assessed the performance of both Schottky diodes and the Silicon Carbide metal oxide semiconductor field-effect transistors (MOSFETs) [2]. The output voltage of the T-type converter while working alone is less than the DC input voltage, and this what triggered the introduction of a boost converter.

There have been two studies [2] [1], which have proven that if the T-type converter is used in combination with other topologies greatly enhances performance. The Jacek et al. [2]version of combining the T-type inverter with a DC-DC inverter has been proved to have low power losses. Sachin et al. have covered the Pulse Width Modulation concept widely, and this concept is used in the Jacek et al. article. One of the challenges that have been mostly encountered with the T-type inverters is the issue of controlling the ever-unstable neutral point voltage, and this, according to Zorig et al. [3] article can be resolved by combining the three-level inverter with another boost converter.

SiC MOSFETs in a T-Type Inverter

Silicon Carbide (SiC) MOSFET gadgets potentially offer a substantial advantage in this context with their lower switching misfortunes, but the benefit of supplanting all switching gadgets in a T-Type inverter with SiC MOSFETs is not direct. The study by [5] investigates this issue by presenting a detailed examination of the utilization of Si and SiC gadgets for a three-level T-type inverter operating in framework tie applications. The study utilizes datasheet values, switching misfortune measurements and calibrated heat sink thermal measurements to explore the semiconductor's limitations in these two alternatives for a T-Type inverter operating at or close to unity influence factor. The results show that supplanting just the DC transport connection switches with SiC gadgets significantly diminishes the semiconductor misfortunes, permitting either the converter influence level or the switching recurrence to be significantly expanded for a similar gadget misfortune. Subsequently, the utilization of SiC MOSFETS for T-Type inverters can be believed to be an attractive and potentially cost-effective alternative, since just two switching gadgets for every stage leg should be overhauled [5].

Predictive power control

Predictive direct power control has explored in other studies and it has found that using the T-Type inverter has increased the control and power and system robustness can increase with high stability and fast dynamic response by using it [6]. Using the T-type converter a three-phase transformerless has developed for the grid-connected PV systems by the authors in another source and the benefit of developing this system is to reduce the cost of transformers, CMV and harmonic filters and revise the system performance and stability [7]. Energy storage has developed using the T-Type three-level inverter by another source, the system correctness has seen because of high-energy storage [8].

T-Type Converter Sub-Systems **(All Members)**

The main tasks involved in this project were figuring the circuitry, the MATLAB simulations, dSPACE, and the testing processes. The Matlab-Simulink models together with dSPACE need to have program code. A program code to control the Pulse Width Modulation (PWM) is developed for the grid experiment. A PV module is modeled also and the whole circuitry is also simulated on the dSPACE. For the real fabrication and circuitry the ground circuitry, T-type circuitry, power supply-grid and the power-stack boards are wired. The first Matlab code run is the Modulated Predictive Control (MPC).

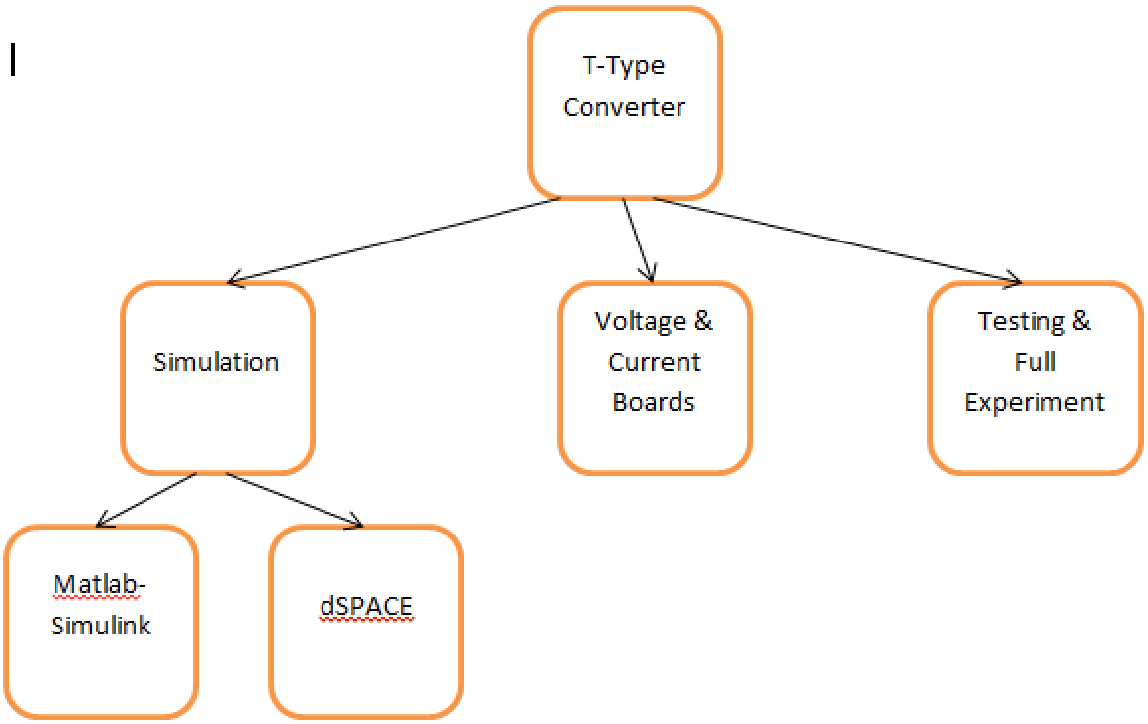


Figure 1: T-Type Converter Sub-systems

Overview of the System Organization **(Abdullah)**

The project is made of dSPACE, Matlab codes, Simulink models of Predictive control and T-Type converter, transformer, and inverters. The subsystems include a step-up transformer, forward biased, reverse biased, DC voltage, oscillator, connect diodes, connect inverter, MATLAB connections, and Test T-converter. The other subsystems are operational modules and a fully develop grid system.

The figure below provides a summary of the mentioned systems

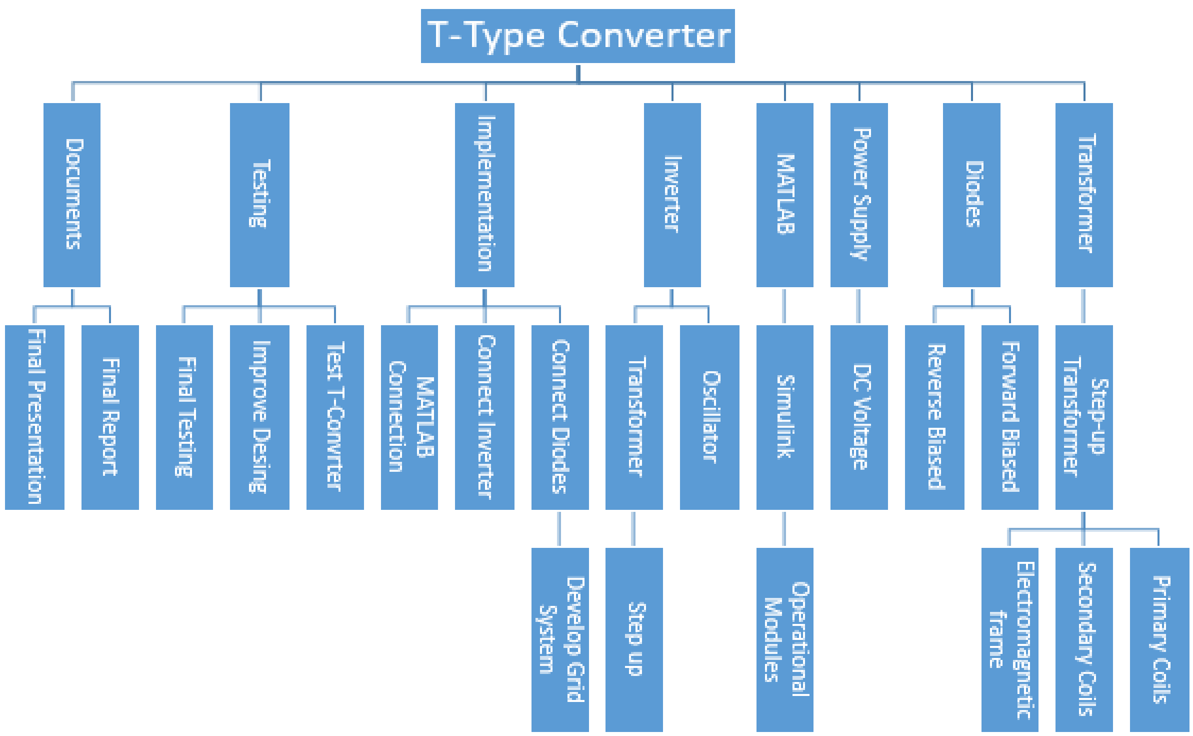


Figure 1: System organization

Before testing our T-type converter and compare the results of its simulations with those of classical control, the MATLAB codes have to be working including all other functions. At various levels, the voltages needed are mostly DC voltages hence the reason why we have transformers, inverters and also the diodes. The transformer developed will be specifically for grid T-type converter and we have to ensure it is able to boost the voltages. The gate drivers are used for interfacing the various parts and also providing readings such as current and voltage which are necessary for the analysis.

In the other subsystems, MATLAB is meant to provide a link between the grid modules and the operational modules through the initialization codes and Simulink models.

Prototypes (Abdullah and Saad)

The prototypes picked includes a transformer, inverters, current and voltage boards, the interface board, and the DSpace. The components were chosen because they have a major role in our project. The entire layout of the project was that the team built the circuit of boards, gate drivers, Dspace. The board was connected to the gate drivers and then D space was connected to the interfaced board and then to the t type converter. The circuit had to be mechanically and electrically sound to enable us to achieve our objective of analyzing the output current, voltage signals, and their ideals.

The step-up transformer was used to increase the voltage and decrease the current at the output and for our project, the step-up transformer was used to modulate the input signal which is quite small. Thus, we had to build an electromagnetic core, and around that core build a copper coil in the form of turns. Two coils on two sides of the transformer, the first side is known as the primary coil and the second side is known as the secondary coil. In a step-up transformer, the number of turns in the secondary coil is large as compared to the number of turns in the primary coil, therefore, it will boost the voltage, and it will reduce the current. This step-up transformer will be interconnected to the Type grid converter during phase 2 of the project. The inverter circuits ensured that the voltage supply to the various modules used in the circuit was up to the needed DC voltage so that it does not affect the integrity of the interfaced parts.

The circuit boards are entirely connected to the gate drivers and subsequently into the DSpace. To visualize the behavior signals, DSpace has to be there and was actually there in the prototypes. We used appropriate wires and jumpers to have it linked to other sub-systems. This enables easy rectification of mistakes and that we were on the right track. With Simulink models already in place, we initialize the Matlab codes and the waveforms could appear. What I have learned about Matlab codes is that it is helpful when developing a system that has several criteria because the parameters of each could be defined and can be adjusted when the expected results are not forthcoming. Another general comment about the Matlab codes is that they are the point. Even before testing the T-type, we confirm that this code was working very well by using the gate drivers since the waveforms could be shown in the Dspace.

The other important from the prototypes is actually the simulation parts that are ideally an outcome from the interaction between the interface board, gate drivers, voltage supply, Simulink models and the software controls i.e. Matlab codes. Firstly, we run the initialization files for Modulated Predictive Control (MPC) for the T-type converter, which were already saved in the Matlab directory files, and it shows fundamental waves that were smooth as compared to that of predictive control. Additionally, they had very low noise. Even though we will still do analyzes at later stages, the initial results show that the team is on the right track and on the verge of fulfilling the client's requirements. In addition, based on what was achieved on the Simulink simulation and oscilloscope output results, the project can be a reliable prototype for the future development of advanced T type inverters. The MPCC and PCC signals displayed on results gave a clear distinction between the models. The prototype will form a basis of research for advanced T-inverters that have advanced power conversion of high quality and reduced harmonics.

At the start of the prototype designing, many concepts were not clear. We had little knowledge of them but we deep researching, things become clearer. This also an important takeaway from the prototypes. Even going forward, research is an important and frequent discussion with teammates is also essential. It helps to uncover many concepts in the project. This actually represents a positive impact of the overall understanding and an advantage to the next phase of implementation. For example, the amount of input voltage signal was unknown to the group. The team had to undertake to assume a certain voltage signal even on Simulink simulation and this was after going through journal articles that described the range of input voltages. The other challenge worth nothing is on the heat sinking which we did drilling badly but we have replacement plans already.

Another learned item in the prototype is how to deal with connections. During physicals assembly, we faced several problems with connecting wires and confusing the ports to plug in. However, with time, we became conversant with the different connectors and we had to order different sets. A very critical sub-system is the materials necessary for the full assembly of the project, the initial suggestion is to look for renowned electrical suppliers that will guarantee as good products, and this is something that we are going to look into at the start of next semester. Also, with connections soldering was another challenging section since the components but this was solved by paying attention and also checking the continuity of the soldered sections.
Lastly, teamwork and professionalism were evident during the prototype phase. The team has worked together on the prototypes; nevertheless, each member of our team was good in some part and bad in another part and we essentially combined efforts to ensure we were on the right track towards realizing the goal of this project. However, at one point one of the members was leading the other one on some prototype and vice versa. For instance, one was good in soldering while the other was good in Matlab coding. The team collaborated effectively and meet on several occasions to deliberate on several concepts. If we carried the team spirit forward, it is no doubt that we will realize project milestones in record time.

Discussion

Multilevel Converter

Multilevel converter have taken over on industrial applications both in medium and higher power levels. The multilevel converters have gained attraction to avoid step-up transformers in every stage which lowers the harmonics in the system. These converter have been widely applied in many sectors, including renewable energy, aviation, and uninterruptible power supplies (UPS) [5].

Multilevel converter have experienced various development through research. It started with a 3 level simple converter, but now it has advanced to higher level with many control methods. This has led to better development in modulation schemes, harmonic reduction, and control methodologies. The objective behind multilevel is to obtain output level voltages by sequence switching of semiconductor switches.

Advantages of Multilevel Converter

The multilevel converter have several advantages, which has to enable its common application in renewable energy sector.

1. Common mode voltage- the multilevel converter has the capability of producing common mode voltage that minimizes the circuit damage.

2. The multilevel converter has the capability of drawing input current with less distortion.

3. The multilevel converter can fundamentally operate higher and lower switching frequencies. This means it can operate with lower loss under low frequency switching.

Multilevel topologies

There various type of multilevel technologies such as;

a. Cascaded H-bridge: This is a type of multilevel converter dated back to 1960s.It uses series-connected H-bridges to offer stepped-up voltage. It is suitable for high power systems because of its modular structure which enables operation of high voltage

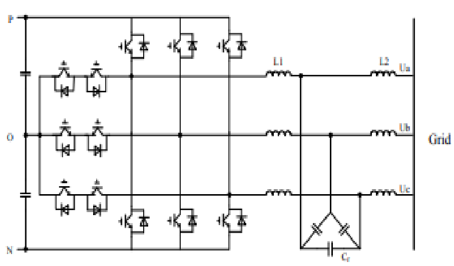
b. Flying capacitor: After the Cascaded topology then flying topology. This topology has gained little access to industry due to ; high switching frequency requirement, the flying capacitor has limiting factor to its lifetime and also voltage is required for initial charging of a flying capacitor.

c. Diode clamped: This is the topology that was introduced in late 1970s, it involve 3 levels Neutral Point clamped topology. This has been widely used in high power applications to its simple implementation and good performance.

T type topology:

T type converter came as an alternative to NPC converter. It has a bidirectional switching mechanism that involve connection of DC link neutral to the midpoint of the converter. Therefore, as compared to NPC it has reduced number of diodes but utilizing the same number of IGBT switches. The design of bidirectional switches can be achieved in several ways; the first method can be achieved by reverse blocking IGBT switches and another one building two conventional IGBT switches in opposite directions. The reverse blocking method is more reliable since it has low switching losses [6].

The basic topology of three level T type converter as shown in fig.1 below



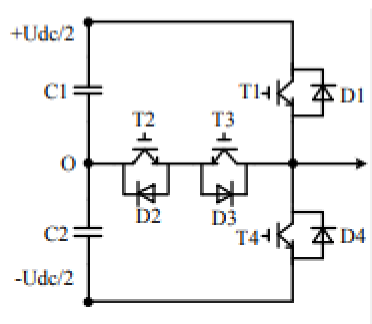


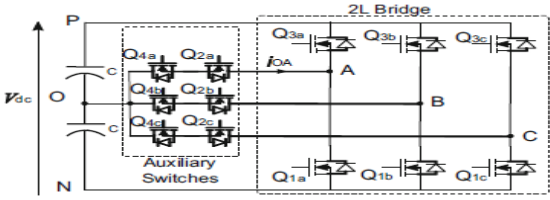
Figure 1 topology of T-NPC

Figure 2 Single-phase of T-NPC

The basic topology of three level T type converter as shown in fig.1 below

Each bridge leg terminal in T-NPC reduces diodes and therefore lowers losses through conduction, and hence operation mechanism is simplified. The other most advantageous factor of NPC is held constant. Putting into consideration the lower link of DC voltage availability in PV system, T-NPC grid-connected PV converter is more efficient and cost-friendly.

3L T-Type Converter Topology



The 3L T-type topology as shown above. It comprises of 2L converter connected to three no series branches of auxiliary switches (semiconductor switches). The principle behind is to clamp the midpoint of DC link with auxiliary switches and thus minimizing the number of elements in current flow path. This essentially improve the efficiency of the converter. In comparison with 3L NPC, the 3L T-type current paths have less number of semiconductor switches for N and P voltage levels achievement [11].

When both series IGBTs connection is turn off simultaneously, the undesirable impact cannot occur in the T-type topology. A three phase 3LT-type enable the implementation of a low level network which can mitigate such transitions or ensure the IGBTs transient voltage is balance out. The reliability of cascaded multilevel converter normally is high and mostly applied in automotive drives. However, the need of many switches and separate dc source for every cell become a major challenge to its applications. The pulse-width modulation PWM is the most suitable way of controlling the output voltage of any converter. The PWM used for multilevel is achieved by intersecting of triangular waveform carrier and modulating signal. Due to long current 3 LT type converter has large current loss through conduction [8].

Efficiency evaluation of 3LT-type

The 3L T-type multilevel converter is higher than that of NPC in a frequency range, less than 7 kHz. According to research done, 3L T type converters have been confirmed to be superior to 3L NPC.

Application of T-type converter on grid system

i. **Two leg T type converter.**

A two leg T type converter is basically applied on a single phase grid connected photovoltaic systems. Even though single phase converter is efficient, it has some losses. The two leg is built when the second leg acts only as the neutral hence reducing the losses and improving quality power.

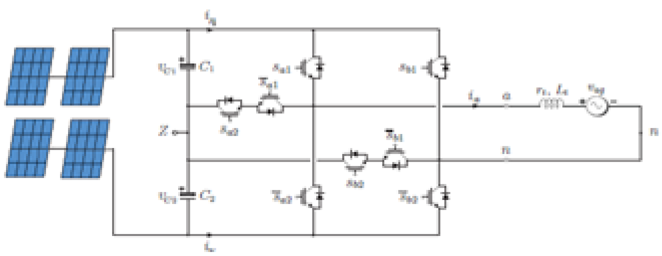


Figure 3 configuration of 2 leg converter

ii. **Three leg T type converter**

A three leg converter is basically a converter using three phase PV and grid connected system. This is the topology which is commonly use with the rest multiphase converters.

iii. **Four leg T type converter**

This converter is applied in three phase four wire system with symmetrical, asymmetrical and nonlinear loads. In comparison with three leg converter, four leg converter provides full utilization of DC bus voltage a lower stress within the DC-link capacitors.

Predictive control of current for grid connected T type Converter (Jafar)

Sampling has become a major challenge of conventional control methods. When the design is run on digital signal processor (DSP), it is noted that there is a delay in filter on sampling hardware and this affect the quality of grid connected current. The method of predictive current control applies the present sampling value of current and predict the future current value. This therefore, eliminates the delays triggered by calculation and sampling process [10].The sampling proposal as shown in figure 4 below where two samples are completed during underflow interrupt and timer cycle interrupt. The most suitable predicted time is Ts/2, Ts representing the switching time.

Status of Planned Features (All members)

The power supply circuitry and the various circuits done have undergone continuity tests to ensure there are no open circuits. We have managed to connect the ground wires, the T-type circuit to the interface board and the whole circuit as achieved in the simulation. The flow of current was as entailed in the manufacturer's instructions. All the wires that need to be soldered have been sorted out. Jumpers were used in instances where soldering was not done, and thereafter power was supplied to the circuit. The correct quantity of the AC and DC were supplied. The continuity tests for the circuit have now been done. The applicable Matlab codes have been developed and the errors debugged to ensure simulation ran smoothly. The Simulink model blocks have been connected together successfully in dSPACE, and the waveforms generated compared with conventional grid converter waveforms. The initial simulation results are ready for analysis, and the open circuit testing on PWM been done. Another test already performed is the testing of the T-type converter on PCC and MPC.

The voltage and current boards interfacing have been done, and they are compatible with our design. The current and voltage readings have been recorded so as to compare the same with the MPC prototype case. All the interface boards have been obtained from the lab and other outlets. The interface boards have been tested for continuity. To test presence of voltage dSPACE and gate drivers have been used to prove this.

Tasks	10-20 Jan	20 Jan – 10 Feb	10 – 17 Feb	17 Feb – 13 Mar	13 – 20 Mar	20 Mar – 6 April	6– 13 April	13 – 27 April
Voltage & Current boards and Interface boards								
Testing of T-type converter with classical control								
MATLAB Results & Data Analysis								
Refining circuitry & PCB design								
Connecting to the grid using a PV model								
Testing of T-type converter with MPC during grid-connection								
A full analysis of the full grid experiment								
Final Report format and Demo								

Figure 2: Timeline of the Tasks

The PV module has been tested using the 2l converter, the PCC and MPC.

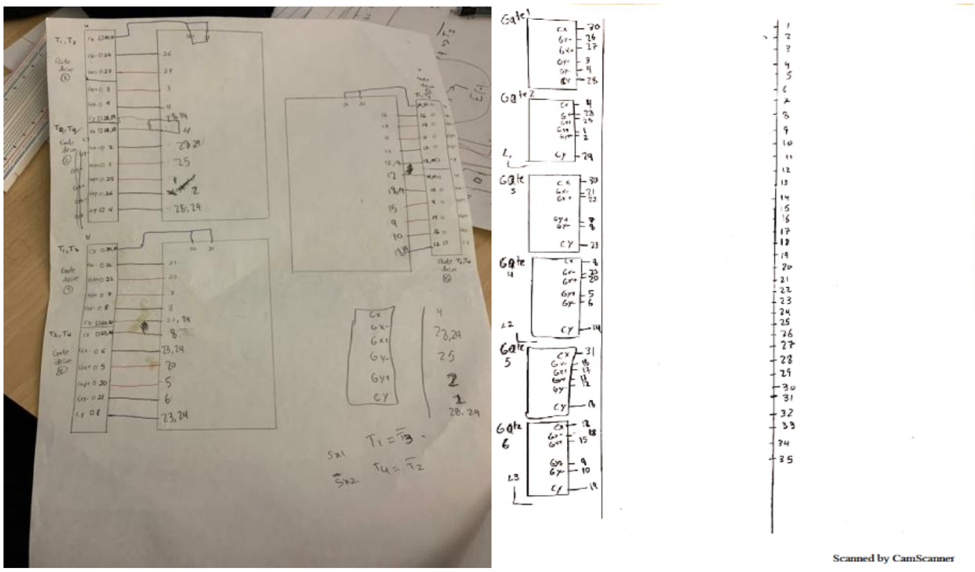


Figure 3: Testing the PCB designs

Challenges

The risks that were encountered were mainly short circuits, breakage of components and developing the Matlab code. The short circuits were a major concern during soldering and wiring process. The soldering and terminal connections are hard to follow in the circuitry. To ensure the circuitry was adhered to we followed the simulation schematics and the manufacturer's instructions. Developing Matlab codes for the simulation was a real challenge as this was a first time process. The voltage and current interfacing boards depend on other subsystems, and this is a challenge when testing the integrity of the interface boards. The short circuits or any open circuits pose a risk to the internally built components of the interfacing board.

Conclusion

In this report, we have widely covered the project components; literature review, a system of the project design, insights from previous prototypes conducted, and project timelines for the next course of action. From the prototype results, it is evident that MPCC control of the T-type had a smooth waveform and low noise outputs as compared to the classical control mechanism. The next phase of our project encompasses testing of the T-type converter in grid-connected system.

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Appendices

Appendix A

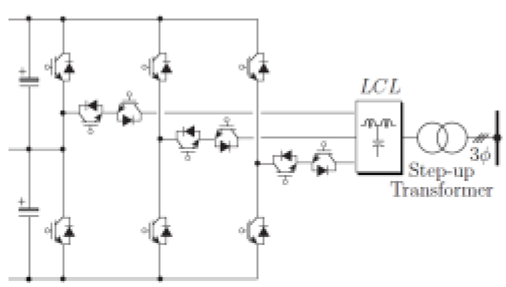

Figure 1: Grid-Connected T-Type Converter

The figure shows a three-legged T-type converter used to connect to the grid DC sources.

Appendix B

Figure 2: Fuji Electric T-type Module

The Fuji Electric module will be used to build the three-phase T-type converter before building the MPC.