A New Transformerless Modular Multilevel Converters (MMC) Based on Half-Bridge Converters at Distribution Level

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Abstract— ***This thesis presents a new family of converters for high power interconnection of dc buses with different voltage levels. Proposed converters achieve high voltage dc-dc conversion without an intermediate ac conversion stage. This function is implemented without series connection of active switches, or the use of isolation transformers. The salient features of proposed converters are (i) design and construction simplicity, (ii) low switching losses through soft turn-on and soft turn-off, (iii) single stage dc-dc conversion without high-current chopping, (iv) modular structure, (v) equal voltage sharing among the converter modules.***

Three converter circuits are investigated. The first performs unidirectional power transfer from a dc bus with higher voltage to a dc bus with lower voltage. The second performs unidirectional power transfer from a dc bus with lower voltage to a dc bus with higher voltage. Both converters are suitable for interconnecting single pole dc buses with same polarity, or double pole dc buses. A third converter is also presented which performs the function of either the first or the second converter with polarity reversal. The third converter is suitable for interconnecting single pole dc buses with different polarities, or double pole dc buses. By hybridintegration of the proposed three converters, the thesis also investigates other topologies for bidirectional power transfer between two dc buses.

Proposed converters operate only in discontinuous conduction mode and exhibit soft switching operation for the active and passive switches. A common feature between the proposed converters is the self current turn-off for the active switches at zero voltage. This allows the use of thyristors as active switches alleviating their reverse recovery losses. For each converter topology, the structure is presented, its operation principle is explained and a complete set of design equations are derived. Comparisons are performed on high-power and high-voltage design examples. The merits and limitations of each converter are concluded. Practical considerations regarding components selection, loss analysis, filter design and the non-idealities of the circuits are studied. Experimental implementation of scaled-down laboratory prototypes is presented to provide a proof of concept and validate the operation principle of the proposed converter topologies.

I. INTRODUCTION

The expanding number of renewable vitality sources and circulated generators requires new systems for the operation and administration of the power matrix with a specific end goal to keep up or even to enhance the power-supply unwavering quality and quality. Also, progression of the matrices prompts new administration structures, in which exchanging of vitality and power is ending up noticeably progressively vital. The power-electronic innovation assumes a critical part in appropriated era and in incorporation of renewable vitality sources into the electrical framework, and it is generally utilized and quickly growing as these applications turn out to be more coordinated with the matrix based frameworks.

Amid the most recent couple of years, power gadgets has experienced a quick development, which is fundamentally because of two variables. The first is the advancement of quick semiconductor switches that are fit for exchanging rapidly and dealing with high powers. The second component is the presentation of continuous PC controllers that can actualize progressed and complex control calculations. These variables together have prompted the advancement of savvy and network well disposed converters.

Renewable vitality source (RES) coordinated at circulation level is named as dispersed era (DG). The utility is worried because of the high infiltration level of discontinuous RES in dissemination frameworks as it might represent a risk to organize as far as dependability, voltage direction and power-quality (PQ) issues. In this way, the DG frameworks are required to agree to strict specialized and administrative structures to guarantee sheltered, solid and productive operation of general system. With the headway in power gadgets and computerized control innovation, the DG frameworks can now be effectively controlled to upgrade the framework operation with enhanced PQ at PCC. Be that as it may, the broad utilization of force hardware based gear and non-direct loads at PCC create symphonious streams, which may break down the nature of force [1], [2].

By and large, current controlled voltage source inverters are utilized to interface the irregular RES in conveyed framework. As of late, a couple control systems for framework associated inverters consolidating PQ arrangement have been proposed. In [3] an inverter works as dynamic inductor at a specific recurrence to ingest the symphonious current. However, the correct computation of system inductance continuously is troublesome and may fall apart the control execution. A comparative approach in which a shunt dynamic channel goes about as dynamic conductance to soggy out the sounds in dispersion system is proposed in [4]. In [5], a control system for renewable interfacing inverter in view of – hypothesis is proposed. In this system both load and inverter current detecting is required to remunerate the heap current sounds [7]. The non-direct load current sounds may bring about voltage music and can make a genuine PQ issue in the power framework arrange. Dynamic power channels (APF) are broadly used to remunerate the heap current music and load unbalance at dissemination level. This outcomes in an extra equipment cost. In any case, in this paper creators have joined the elements of APF in the, customary inverter interfacing renewable with the matrix, with no extra equipment cost. Here, the fundamental thought is the greatest usage of inverter rating which is more often than not underutilized because of discontinuous nature of RES [8].

II. Mutltilevel Inverter Structures

A. Importance of multilevel inverter

A power inverter, or inverter, is an electronic device or circuitry that changes direct current (DC) to alternating current (AC). The input voltage, output voltage and frequency, and overall power handling depend on the design of the specific device or circuitry.

The importance of multilevel inverters has been increased since last few decades. These new types of inverters are suitable for high voltage and high power application due to their ability to synthesize waveforms with better harmonic spectrum and with less Total Harmonic Distortion (THD). Numerous topologies have been introduced and widely studied for utility of non-conventional sources and also for drive

B. Main feature of Multi-Level Inverter (MLI)

1. Ability to reduce the voltage stress on each power device due to the utilization of multiple levels on the DC bus.
2. Important when a high DC side voltage is imposed by an application (e.g. traction systems).
3. Even at low switching frequencies, smaller distortion in the multilevel inverter AC side waveform can be achieved (with stepped modulation technique).

C. Advantages of Multi-Level Inverter (MLI)

A multilevel converter has several advantages over a conventional two-level converter that uses high switching frequency pulse width modulation (PWM). The attractive features of a multilevel converter can be briefly summarized as follows.

1. Staircase waveform quality: Multilevel converters not only can generate the output voltages with very low distortion, but also can reduce the dv/dt stresses; therefore Electro Magnetic Compatibility (EMC) problems can be reduced.
2. Common-Mode (CM) voltage: Multilevel converters produce smaller CM voltage; therefore, the stress in the bearings of a motor connected to a multilevel motor drive
3. Input current: Multilevel converters can draw input current with low distortion.
4. Switching frequency: Multilevel converters can operate at both fundamental switching frequency and high switching frequency PWM. It should be noted that lower switching frequency usually means lower switching loss and higher efficiency.

Unfortunately, the multilevel converters do have some disadvantages. One particular disadvantage is the greater number of power semiconductor switches needed. Although lower voltage rated switches can be utilized in a multilevel converter, each switch requires a related gate drive circuit [40]. This may cause the overall system to be more expensive and complex. Plentiful multilevel converter topologies have been proposed during the last two decades. Contemporary research has engaged novel converter topologies and unique modulation schemes.

In recent years, new industrial applications for medium and high voltage motors (which may require voltages in megawatts ranges) applied these inverters which can be used as an alternative to the power of a multilevel converter for high and medium renewable energy sources. The use of multilevel converters has been started since 1975, which is in fact the development of the two-level converters. Purpose of the use of multilevel converters, access to a high power is the key to a series of semiconductor strength and low DC voltage sources for energy conversion based on elements such as capacitors, batteries and renewable energy sources is implemented. Using the appropriate switching and considering several sources of input DC converters, high voltage can be obtained in a multilevel converter output. Multilevel converters have advantages and disadvantages compared to two level converters considering switching frequency and Pulse Width Modulation (PWM) can include. 1- Quality of the AC output waveform: a multilevel converter cannot only produce a voltage output with extremely low distortion, also capable of decreased stress dv /dt. So the problem of electromagnetic interference (EMI) can be reduced. 2 - Less Common Mode voltage (CM): less CM voltage multilevel converters and therefore less stress on the motor bearings as well as semiconductor components connected to a multi-level inverter will be reduced. 3 - The input source: the use of multilevel converters can already having low distortion input sources, problems related to power quality in distribution systems to overcome. 4 - Switching frequency: multilevel converters can be both primary and high switching frequency to be used. Lower switching frequency usually means higher efficiency as well. The disadvantages of multilevel converters can also be summarized as follows: 1 - To be expensive due to the high number of switching elements (which cannot be economically affordable.) 2 - Design complexity due to the lack of sufficient knowledge (creates problems) 3 - Different techniques for controlling converters, multilevel provided. Example can be pulse width modulation sine, eliminating the harmonic selective modulation vector space mentioned. Most important applications of inverters multilevel can to drive motors, medium voltage, transmission systems AC flexible and renewable energy sources are connected to the grid . In this section, the advantages and disadvantages of multilevel converters, kind of actives switch usage, how to charge and discharge the closing of diodes and capacitors of the converter structure and especially for the inverter connected to the grid will be reviewed

III. Modular Multilevel Converter

3.1 Description and principle of operation of MMC

The typical structure of a MMC is shown in Fig. 2, and the configuration of a Sub-Module (SM) is given in Fig. 3. Each SM is a simple chopper cell composed of two IGBT switches (T1 and T2), two anti-parallel diodes (D1 and D2) and a capacitor C.

Each phase leg of the converter has two arms, each one constituted by a number N of SMs. In each arm there is also a small inductor to compensate for the voltage difference between upper and lower arms produced when a SM is switched in or out.

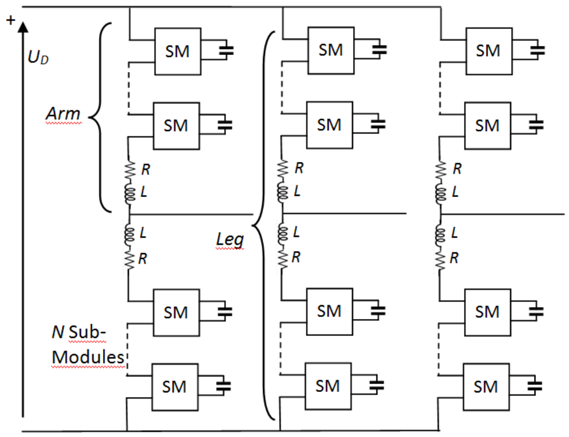


Figure 3.1 - Schematic of a three-phase Modular Multi-level Converter

With reference to the SM shown in Fig. 3.1 the output voltage UO is given by,

UO = UC if T1 is ON and T2 is OFF

UO = 0 if T1 is OFF and T2 is ON

where UC is the instantaneous capacitor voltage.

The configuration with T1 and T2 both ON should not be considered because it determines a short circuit across the capacitor. Also the configuration with T1 and T2 both OFF is not useful as it produces different output voltages depending on the current direction. Fig. 3.2 shows the current flows in both useful states. In a MMC the number of steps of the output voltage is related to the number of series connected SMs. In order to show how the voltage levels are generated, in the following, reference is made to the simple three level MMC configuration shown in Fig. 3.3.

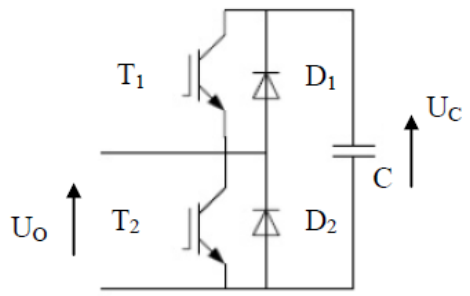


Figure 3.2 – Chopper cell of a Sub-Module

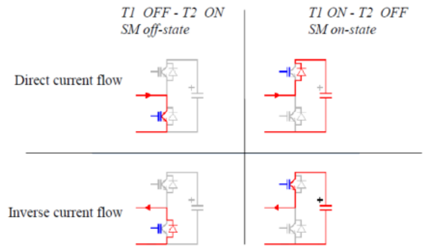


Figure 3.3 - States of SM and current paths

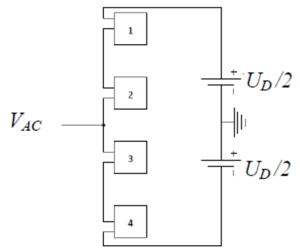


Figure 3.4 - Schematic of one phase of Three-Level Converter

In this case, in order to get the positive output, +UD/2, the two upper SMs 1 and 2 are bypassed. Accordingly, for the negative output, - UD/2, the two lower SMs 3 and 4 are bypassed. The zero state can be obtained through two possible switch configurations. The first one is when the two SMs in the middle of a leg (2 and 3) are bypassed, and the second one is when the end SMs of a leg (1 and 4) are bypassed. It has to be noted that the current flows through the SMS that are not by passed determining the charging or discharging of the capacitors depending on the current direction. Therefore, in order to keep the capacitor voltages balanced, both zero states must be used alternatively. The voltage waveform generated by the three level converters is shown in Fig. 3.5

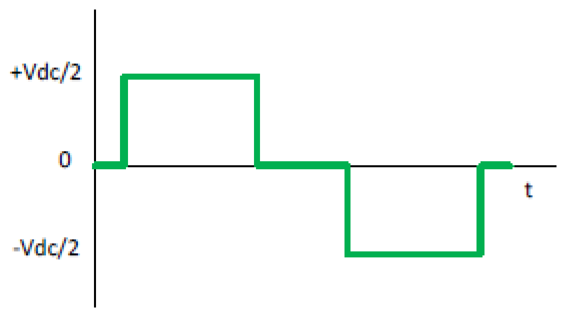


Figure 3.5 - Voltage waveform of a Three-Level Converter.

The principle of operation can be extended to any multi-level configuration as the one represented in Fig. 3.6

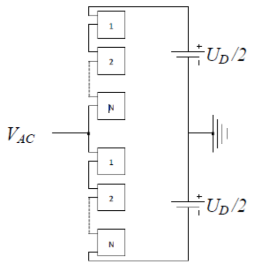


Figure 3.6 - Schematic of one phase of Multi-Level Converter.

In this type of inverter, the only states that have no redundant configurations are the two states that generate the maximum positive and negative voltages, + UD/2 and –UD/2. For generating the other levels, in general there are several possible switching configurations that can be selected in order to keep the capacitor voltages balanced. In MMC of Fig.3.5, the switching sequence is controlled so that at each instant only N SMs (i.e. half of the 2N SMs of a phase leg) are in the on-state. As an example, if at a given instant in the upper arm SMs from 2 to N are in the on-state, in the lower arm only one SM will be in on-state. It is clear that there are several possible switching configurations. Equal voltage sharing among the capacitor of each arm can be achieved by a selection algorithm of inserted or bypassed SMs during each sampling period of the control system. A typical voltage waveform of a multi-level converter is shown in Fig. 3.7.

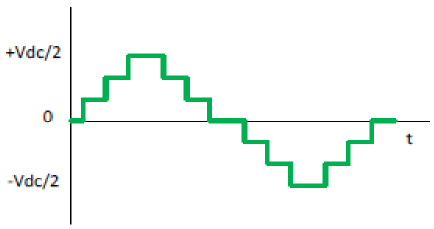


Figure 3.7 - Voltage waveform of a Multi-Level Converter

IV. Modular Multilevel Converter Modeling

Introduction

This chapter presents the modeling approach for illustrating the operation principles of Modular Multilevel Converters (MMC) including the MMC with half-bridge power cells and the Alternate-Arm Converter (AAC). Modular multilevel converters have emerged as new multilevel converters that can be used especially in High Voltage Direct Current (HVDC) and Medium Voltage Direct Current (MVDC) applications [25],[39-42]. Generally, the main advantages of the MMC with as compared to other types of multilevel converters are their high modularity and cabability for high voltage scalability, which means that they can be connected directly to the grid without using any transformer [43]. The modular multilevel converter structure is shown in Figure 2-1. The MMC generally consists of upper and lower arm power cells, which can be half-bridge or full-bridge. The first model of the MMC was generated by replacing the single switches in a two-level converter with a series of power modules. As mentioned, these power modules can be half-bridge or full-bridge; however, due to the higher number of switches and switching power losses, MMC with half-bridge is more oftren developed. In order to eliminate inrush current during switching between modules, additional inductors should be added in series with the power modules in each arm [44].To have sinusoidal output voltage, the upper arm and lower modules' references should be justified with respect to the DC voltage in order to generate a proper wave-shaping circuit [29]. In the MMC with the half-bridge, the maximum voltage over each module is the DC-link voltage divided by the number of arm modules; however, the MMC with the full-bridge module can work in over-modulation since each module can generate negative voltage as well [45].

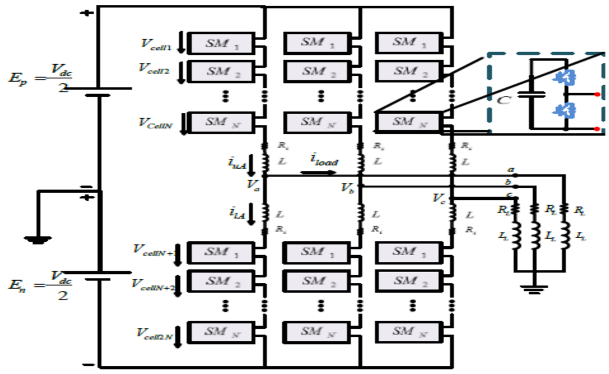


Figure : Modular Multilevel Converter topology with each sub-module structure.

One of the disadvantages of the MMC is the existence of relatively high circulating current due to the difference in voltage of the arm inductors [46]-[47]. To limit the circulating current, the arm inductor size should be selected to be quite high or the circulating current suppressing controller should be employed [48]. Another issue regarding this topology is the number of capacitor banks required for each module in the MMC, which can lead to a huge space occupied by capacitors and cause reliability issues
[49]-[50].] Moreover, having a high number of modules makes the control system more complex [51]. Significant efforts have been dedicated to the modeling of the MMC and to a circuit behavior analysis of the converter. Different modeling approaches for the Modular Multilevel Converter (MMC) have been carried out in the literature. In [52], the state-space switching model of the MMC is developed and the complete derivation procedure of that is given. In reference [53], a continuous model of a three phase MMC, which is derived from ordinary differential equations, is developed and described. All the other existent models deal with the three-phase average model of the MMC, and the equations are extracted based on the average model [52-57].
In this chapter, a new modeling approach based on D-Q frame modeling is proposed for use as a model-based converter of the inner and outer loop control design. DQ modeling of the MMC can provide the relations of the duty cycles and arm quantities as well as the output voltage and current of the converter. Also, the proposed DQ model of the MMC is of great value in developing new control methods for the MMC. To obtain the DQ model, the following procedure should be

taken. First of all, a three-phase average model of the converter should be derived from the switching model. Then by applying the Park transformation, the DQ model can be achieved. The second order harmonic circulating current is considered as the dominant component of the circulating current and higher order harmonics are considered to be negligible [47]. Therefore, the MMC system can be divided into three-frames of operation: DC, fundamental frequency, and twice the fundamental frequency frame. By assuming the superposition, each of the parameters can be modeled in these three-frames and finally the results can be added together. Indeed, using this model, DC current and circulating current equations can be
decoupled from the load current. By changing the modeling of MMC into three separate models, one will be able to derive the DQ model in each case.

Modular Multilevel Converter Modeling (MMC)
MMC Switching Model

The general state-space switching model is derived based on the simplest MMC configuration: a single-module MMC topology as shown in Figure 2-1 [52]. The state-space model is derived by selecting the inductor currents and capacitor voltages as states of the converter for control purposes. Therefore, five totally independent KVL equations can be written for the converter and iUabc (Upper Arm Current phase a, b and c), iLabc (Lower Arm Current phase a, b and c) can be chosen as initial independent state variables. However, the DC current, line currents and circulating currents are the most convenient parameters to describe and control the operation of the converter, and the fundamental circuit characteristics of the MMC can be better reflected based on them. Hence, the initial state variables should be changed into another set of independent states in terms of the three latter current components. Figure 2-2 shows the switching model of the MMC.

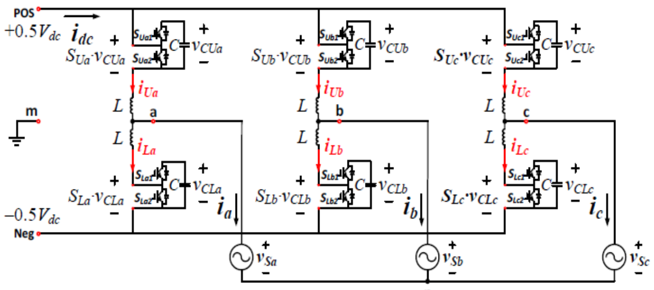
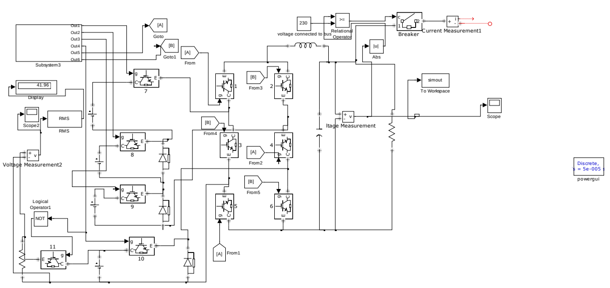
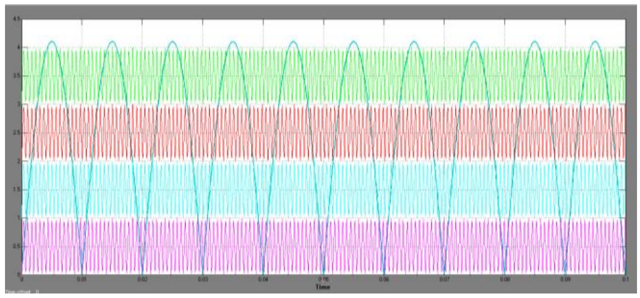


Figure : Switching Model of the MMC.

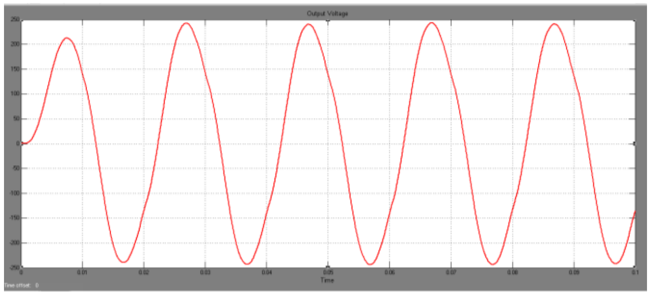
V. Simulation Results



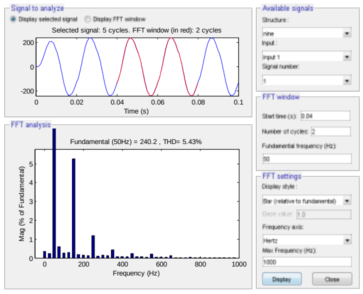
Simulation Circuit of Nine Level MMC



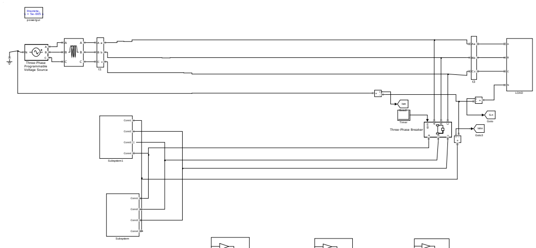
Level Shifted PWM Technique with Full wave converter



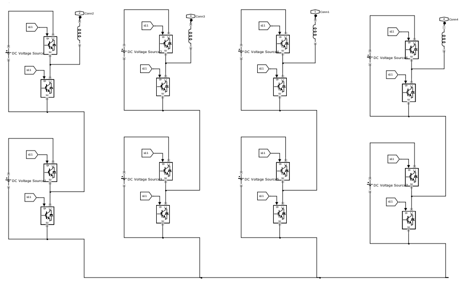
Output voltage of MMC



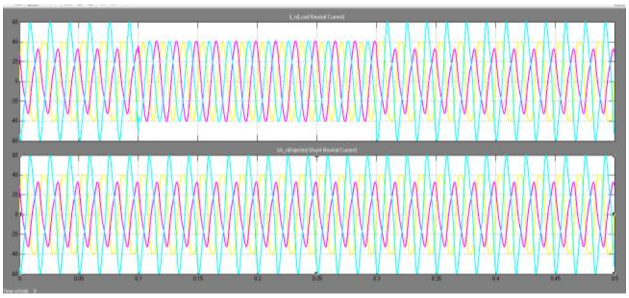
THD Analysis of output Voltage



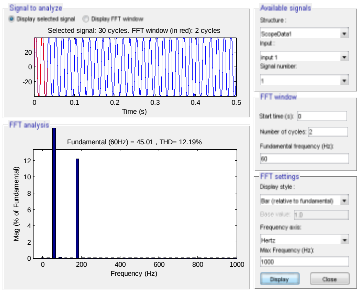
Proposed Simulation Circuit



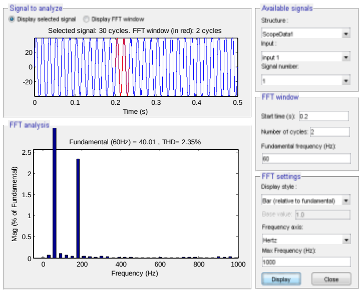
Half Bridge MMC



Load Current and Injected current



THD Analysis of Load Current when MMC is not connected to distribution system (12.19%)



THD Analysis of Load Current when MMC is connected to distribution system (2.35%)

VI. CONCLUSION

A new transformerless four-leg topology is suggested for shunt compensation, the modular multilevel converters (MMC) based on the half-bridge converters, to achieve higher performance a STATCOM in a distorted and unbalanced medium voltage large-current (MV-LC) system. Both proposals can be controlled for various purposes such as reactive power and unbalance compensation, voltage regulation, and harmonic cancellation. Moreover, related control strategies are also suggested for both the MMC and the EMMC to ensure that the source-end three-phase currents are sinusoidal and balanced. Also, the dc-link capacitors of the half-bridge converters are regulated. One interesting application for the EMMC-based STATCOM could be the improvement in power quality and performance of the electrified railway traction power supply system.

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