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A NOVEL TRANSFORMERLESS SHUNT COMPENSATION WITH MODULAR MULTILEVEL CONVERTER

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ABSTRACT
Nowadays, it is problematic to connect only one power semiconductor switch directly to the grid due to the high voltage range. In order to solve this difficulty, a new type of power converter has been introduced as a solution in high power applications. Multilevel Converters use high speed switching components, avoiding the problem of linking them directly to the grid by connecting single devices among multiple DC levels. Different Multilevel topologies have been developed in the last few years. The latest and most promising such topology for high power applications is the Modular Multilevel Converter (MMC). The Modular Multilevel Converter represents an emerging topology with a scalable technology making high voltage and power capability possible. The MMC is built up by identical, but individually controllable sub modules. Therefore the converter can act as a controllable voltage source, with a large number of available discrete voltage steps. This characteristic complicates the modeling both mathematically and computational. A transformer less shunt compensator (STATCOM) based on a modular multilevel converter introduces a new time-discrete appropriate current control algorithm and a phase-shifted carrier modulation strategy for fast compensation of the reactive power and harmonics, and also for the balancing of the three-phase source side currents. The performance of the proposed STATCOM implemented using MATLAB/Simulink.

Keywords: *Modular Multilevel Converter (MMC), Transformer less shunt compensator (STATCOM),Voltage Source Inverter.*

1. INTRODUCTION

In recent years, the need for high power apparatus has been derived by numerous industrial applications. Medium voltage motor drives and utility applications are some examples, since they require medium voltage and megawatt power level. Another application regards medium voltage grids, where it is troublesome to connect only one power semiconductor switch directly. As a result, several multilevel power converter structures have been introduced as an alternative in high power and medium voltage applications. Multilevel converters not only achieve high power ratings, but also enable the use of renewable energy sources. Photovoltaic and wind energy sources as well as fuel cells can be easily interfaced to a multilevel converter system for a high power application. During the last years, several multilevel converter topologies have been developed. The elementary concept of a multilevel converter was to achieve higher power by using a series of power semiconductor switches with several lower voltage DC sources to perform power conversion by synthesizing a staircase voltage waveform. Capacitors, batteries, and renewable energy voltage sources can be used as the multiple DC voltage sources. The commutation of the power switches aggregates these multiple DC sources in order to achieve high voltage at the output.

Multilevel converters show several advantages over conventional two-level converters. Some of the most attractive features of multilevel converters are briefly summarized as follows. Staircase waveform quality: Multilevel converters generate output voltages with much lower harmonic content and reduce the dv/dt stresses. Therefore electromagnetic compatibility (EMC) problems can be reduced. Common mode (CM) Voltage: Multilevel converters produce smaller CM voltage. The stress in the bearings of a motor connected to a multilevel motor drive, for example, can be therefore reduced. Furthermore, through the use of advanced modulation strategies, CM voltage can be eliminated.

Multilevel converters have some disadvantages as well. One particular disadvantage is the greater number of power semiconductor switches needed. This usually leads to a more complex overall system and more conducting losses. There are many multilevel converter topologies, which have been proposed in literature during the last two decades. Three major structures are the following: *(a)* Diode-Clamped (Neutral-Clamped), *(b)* Flying-Capacitors (Capacitor-Clamped) and *(c)* Cascaded H-bridge and *(d)* Modular Multilevel Converters (MMC). Moreover, abundant modulation techniques and control paradigms have been developed for multilevel

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converters, such as sinusoidal pulse width modulation (SPWM), selective harmonic elimination (SHE-PWM) and space vector modulation (SVM).Multilevel converters are found in applications such as industrial medium-voltage motor drives, utility interface for renewable energy systems, flexible AC transmission system (FACTS), traction drive systems and high-voltage direct current interconnection and transmission (HVDC).

2. OPERATION PRINCIPLE OF MODULAR MULTILEVEL CONVERTER (MMC)

The series connection of a number of capacitors that can be connected or bypassed could be represented as a continuous, biased, AC voltage source. The sum of the voltages in these controllable voltage sources in one phase leg has to be equal the DC link voltage. Therefore, if the value of the upper voltage source increases, the voltage source value in the lower arm should decrease respectively and vice versa. Feeding active power from the leg in not necessary; it is favorable to transfer if from the DC side to the AC side and vice versa through temporary storage in capacitors. This brings along some problems due to the fact that capacitors do not assure a constant voltage while connected. The capacitor voltages will vary depending the direction of the current. One solution to this problem is to add an auxiliary control circuit for charging or discharging the capacitors while they are not connected. This brings more complication and cost to the whole system. The correct solution is to use the effect that charges and discharges the capacitors through the modulation in order to keep them balanced. However, the inconsistence of the capacitor voltages has to be also taken into account, for which there are employed inductances in each arm of the configuration. The final single-phase MMC circuit is shown in Figure 2.9 and the respective three-phase in Figure 2.8.

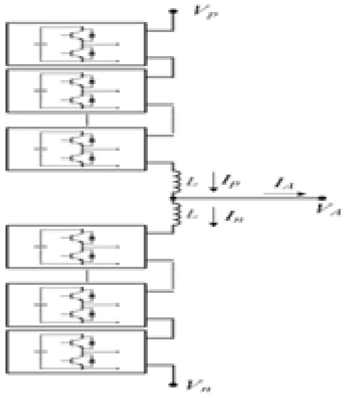

Figure 2.8. System Configuration

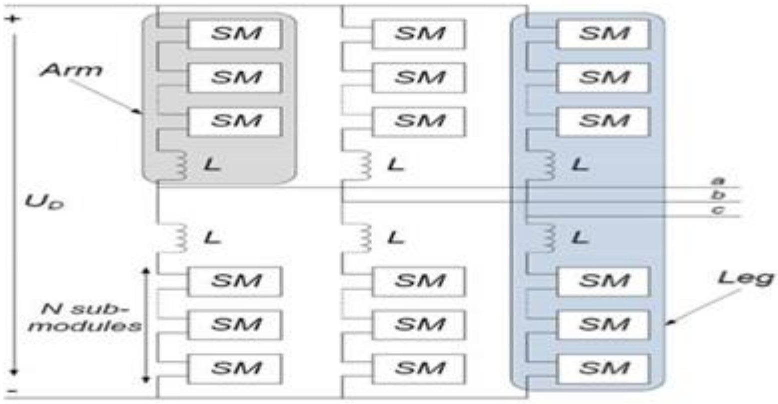

Figure 2.9. Inverter's Leg configuration

Advantages:

- Effective switching frequency =actual switching frequency*number of modules per phase leg so this significant reduction of switching losses
- No need for bulk filters at the ac side

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- Modularity-Redundancy due to the extra Modules that can be inserted to substitute the failed ones
- Simple mechanical construction
- Lower voltage ratings for the semiconductors
- Scalability: No DC-link voltage limitation
- Possibility to by-pass a faulted module and not trip the Converter
- Stepwise change in the output voltage reducing the Electromagnetic Interference(EMI)

3. CONTROL STRATEGIES FOR MULTILEVEL CONVERTERS

When the three-phase four-wire systems are used to feed three-phase unbalanced loads, negative and zero sequence components of the source currents will appear, helping degrade the performance of equipments such as transformers, electrical machines and others. For non-linear loads, therefore, the source currents will contain unbalanced fundamental and harmonic components. In this case, even with perfectly balanced single-phase non-linear loads, a third harmonic component and its multiples will flow through the neutral wire. Moreover, an excessive zero sequence current can help cause damage in the neutral conductor. The compensation algorithms used to extract the three-phase reference currents are based on the synchronous reference frame (SRF) method . Although the SRF method is based on the balanced three-phase loads, it can also be used for single-phase loads, allowing independent control of all three phases. The flexibility to choose the SRF-based controller strategy will determine if the negative, zero or both sequence current components will be compensated. The SRF-based algorithms will be evaluated under unbalanced load conditions and will be applied to three shunt APF topologies, split-capacitor, four-leg three F-Bridge and half bridge multilevel converters.

4. SYNCHRONOUS REFERENCE FRAME CONTROL

The synchronous reference frame or the Park transformation system maps the three-phase current and voltage components in the abc phases into the current and voltage components on the dq0 reference frame. The Park variables transformation matrix applied to three-phase voltages and currents components is shown below in matrix form as:

$$T_{dq0}^{abc} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ -\sin\theta & -\sin(\theta - 2\pi/3) & -\sin(\theta + 2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \quad (4.1)$$

where θ is the rotating coordinate angle, which can be chosen as constant or linear time-varying for different objectives. The inverse matrix of (4.1) is calculated by (4.2).

$$T_{123}^{dq0} = (T_{dq0}^{123})^{-1} = (T_{dq0}^{123})^{T} = 2/3\begin{bmatrix} \cos\theta & \sin\theta & \frac{1}{2} \\ \cos(\theta - 2\pi/3) & \sin(\theta - 2\pi/3) & \frac{1}{2} \\ \cos(\theta + 2\pi/3) & \sin(\theta + 2\pi/3) & \frac{1}{2} \end{bmatrix} \quad (4.2)$$

We define the Park transformed variables X^{dq0} of a three-phase abc signal X^{abc} as:

$$X^{dq0} = T_{dq0}^{abc} X^{abc} \quad (4.3)$$

As mentioned in previous section, by use of synchronous reference frame control, the grid current and voltage components transform into a reference frame that rotates synchronously with the grid voltage. By means of this technique, the control variables values become dc values; thus, filtering and controlling can be achieved easily. As an example, a simple schematic diagram of the synchronous reference frame control is shown in figure 3.2. As shown in this model, the dc side voltage is controlled and regulated in accordance to the necessary output power of converter in ac side. It can be seen that, its output is the reference current for the circuit of active current controller, whereas the reference current for the reactive current is usually set to zero, if the reactive power control is not allowed.

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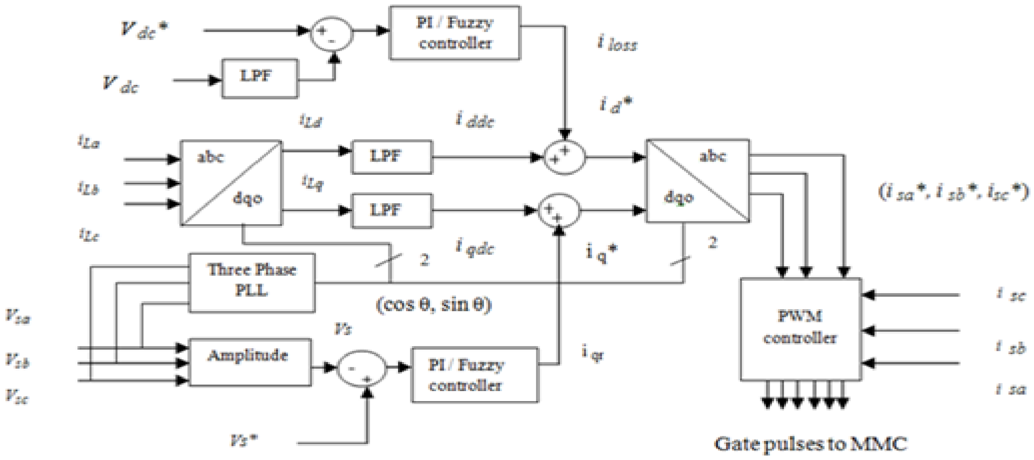

Figure 4.2: General schematic diagram for synchronous reference frame control structure

The synchronous reference control scheme is generally associated with proportional-integral (PI) controller since it has an acceptable behavior when regulating dc variable components. The matrix transfer function of the controller in dq coordinates can be expressed as:

$$G_{PI}^{dq}(s) = \begin{bmatrix} k_p + \frac{k_i}{s} & 0 \\ 0 & k_p + \frac{k_i}{s} \end{bmatrix} \quad (4.4)$$

Where k_p the proportional is gain and k_i is the integral gain of the PI controller.

Stationary Reference Frame Control

The Stationary reference frame or the Clarke transformation system maps the three-phase instantaneous current and voltage components in the abc phases into the instantaneous current and voltage components on the αβ0 reference frame. The Clarke variable transformation matrix of three-phase components is defined as:

$$T_{\alpha\beta 0}^{abc} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \quad (4.5)$$

The inverse matrix of (4.5) can be expressed as:

$$T_{abc}^{\alpha\beta 0} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \quad (4.6)$$

We define the Clarke transformed variables $Y^{\alpha\beta 0}$ of a three-phase abc signal Y^{abc} as:

$$Y^{\alpha\beta 0} = T_{\alpha\beta 0}^{abc} Y^{abc} \quad (4.7)$$

Calculation of Reference Currents

Figure 4.3 shows the voltage and current components vectors of MMC model which shown in stationary and rotating synchronous reference frames.

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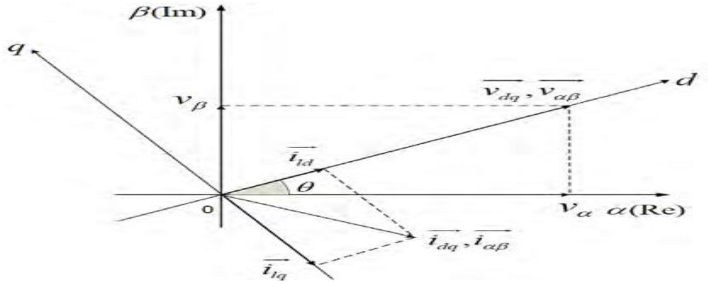

Figure 4.3: Voltage and current components in stationary and rotating synchronous reference frame

The transformation matrix (αβ/dq) which is based on park equations is given in

$$\begin{bmatrix} i \\ i \end{bmatrix} = T. \begin{bmatrix} \end{bmatrix}, \text{ and } \begin{bmatrix} v \\ v \end{bmatrix} = T. \begin{bmatrix} 1 \\ 1 \end{bmatrix} \quad (4.8)$$

Where $T = \begin{bmatrix} \cos\theta & \sin \\ -\sin\theta & \cos \end{bmatrix}$, and the inverse matrix is $T = (T_{dq}^{\alpha\beta})$^ - .

ı, ı, i_{ld}, and are d and q component of voltages and currents in rotating synchronous reference frame, respectively, and is the instantaneous angle of load voltage or voltage at the PCC.

According to Fig. 4.3, the d-component of the voltage in stationary and rotating synchronous reference frame is as follows:

$$v_d = |v_{dq}| = |v_{\alpha\beta}| = \sqrt{v_\alpha^2 +} \quad (4.9)$$

and taking in to considerations $i_{l1} = -(i_{l2} + i$

$$\begin{bmatrix} i_{ld} \\ i_{lq} \end{bmatrix} = \sqrt{2}. \begin{bmatrix} \sin(\theta + \pi/3) & \sin\theta \\ \cos(\theta + \pi/3) & \cos\theta \end{bmatrix} \begin{bmatrix} i \\ i \end{bmatrix}. \quad (4.10)$$

By (4.10), d and q components of currents in rotating synchronous reference frame can be calculated by means of current components in 123 variable systems.

5. SIMULATION ANALYSIS AND RESULTS

The three-leg MMC based STATCOM connected to a three-phase four-wire system is modeled and simulated using the MATLAB with its Simulink. The ripple filter is connected to the STATCOM for filtering the ripple in the PCC voltage. The three-phase source, and the shunt-connected three-leg MMC are connected as shown in Fig. 5.1

MATLAB model of the three-leg MMC based STATCOM connected system with linear loads and non-linear loads is shown in below

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figures.

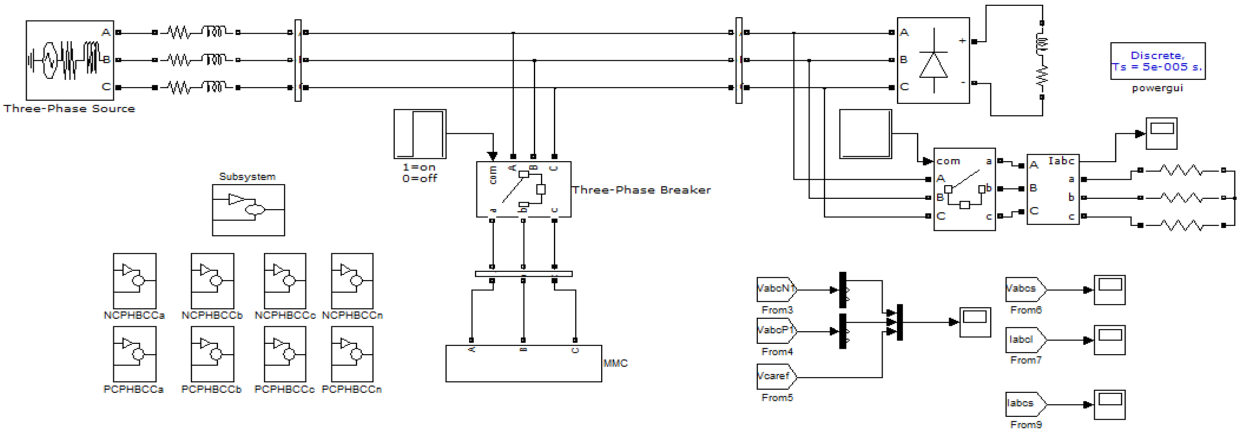
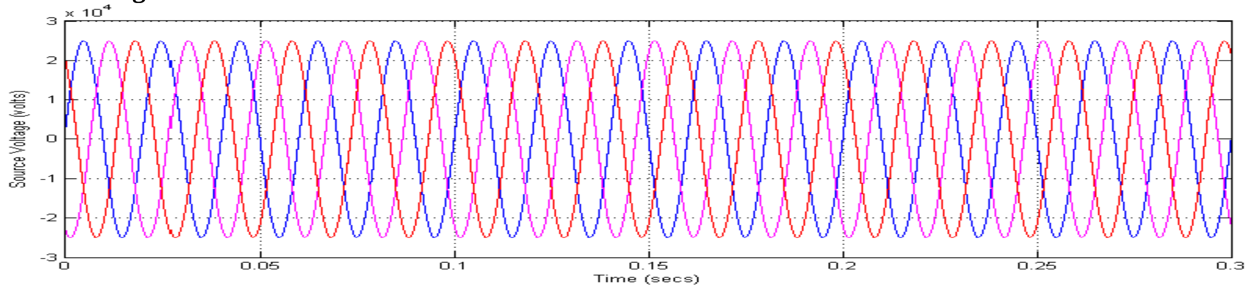


Fig.5.1.Simulation model of the three-leg MMC based STATCOM connected with distorted and non linear loads

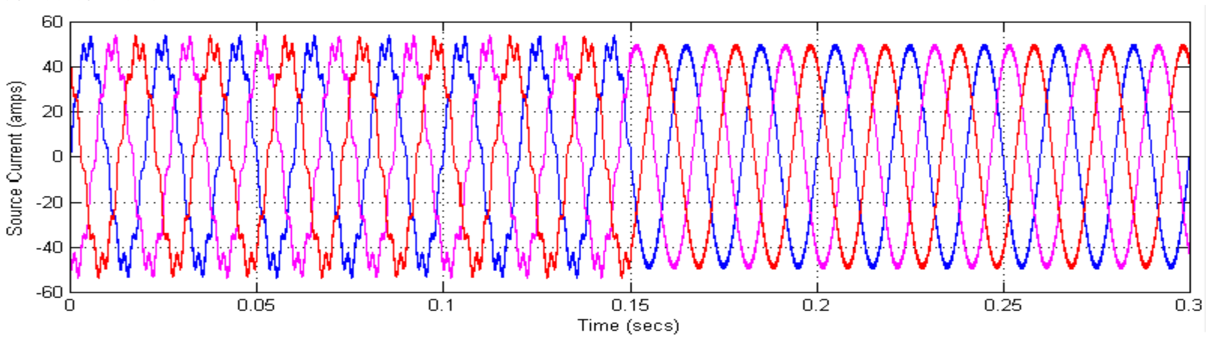
Performance of CHB based STATCOM with Non Linear Load for Compensation of source currents

Source voltage



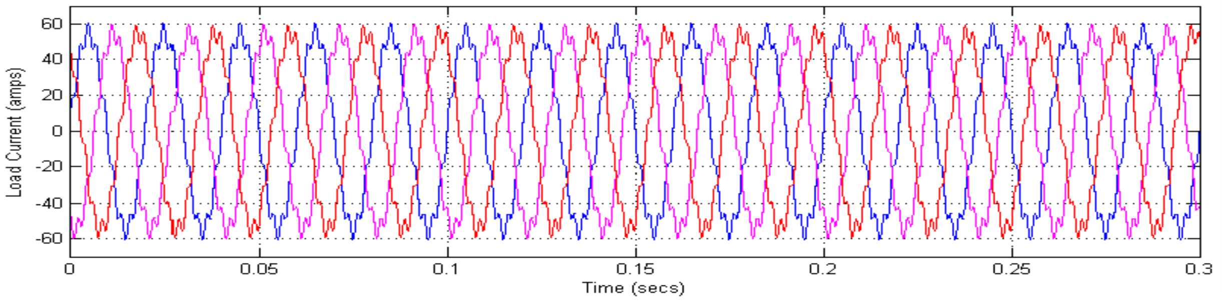
(a)

Source current



(b)

Load current



(c)

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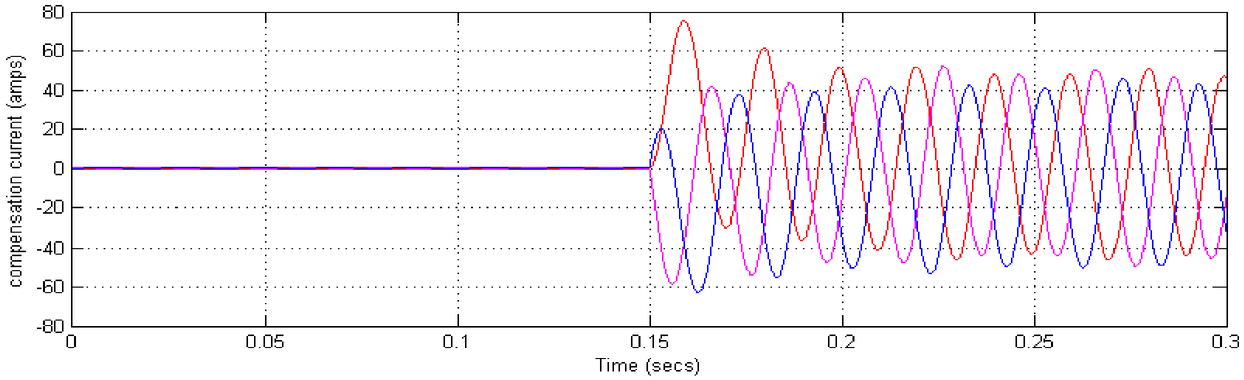
Compensated current



(d)

Fig.5.4 (a) Source voltage (b) Source current (c) Load current (d) Compensated current

The dynamic performance of the CHB based STATCOM with nonlinear and unbalanced load is given in Fig.5.4. It is observed that the harmonic current is compensated and the source currents are balanced and sinusoidal. source current before compensation (time period (0- 0.15sec) and after compensation (time period 0.15- 0.3sec) is given in fig 5.4(b).

Performance of CHB based STATCOM with additional load (t=0.15sec) for Compensation of source current

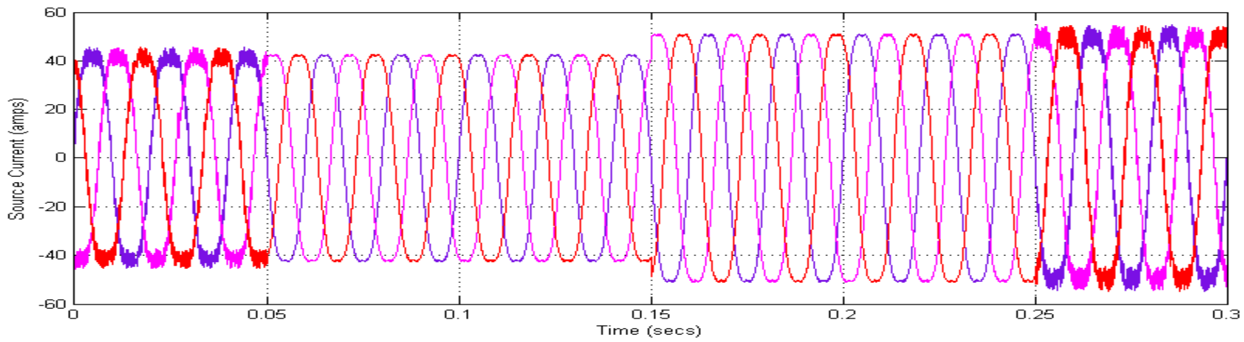


Figure: 5.5 compensated source current using CHB converter (additional Load)

Figure 5.5 shows an additional non linear load was connected at t=0.15 sec and disconnected at t=0.25 sec. The CHB based STATCOM is connected at t=0.05sec at this time the source current was compensated by statcom currents and reduces the harmonic component in source current.

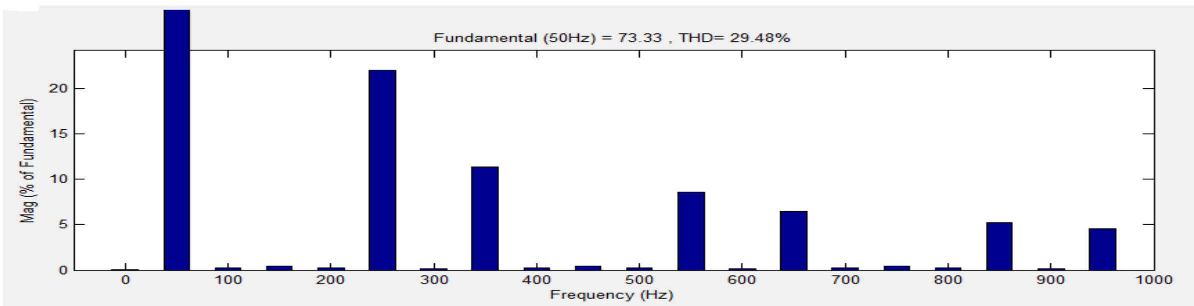


Figure: 5.6 THD of Load Current Spectra

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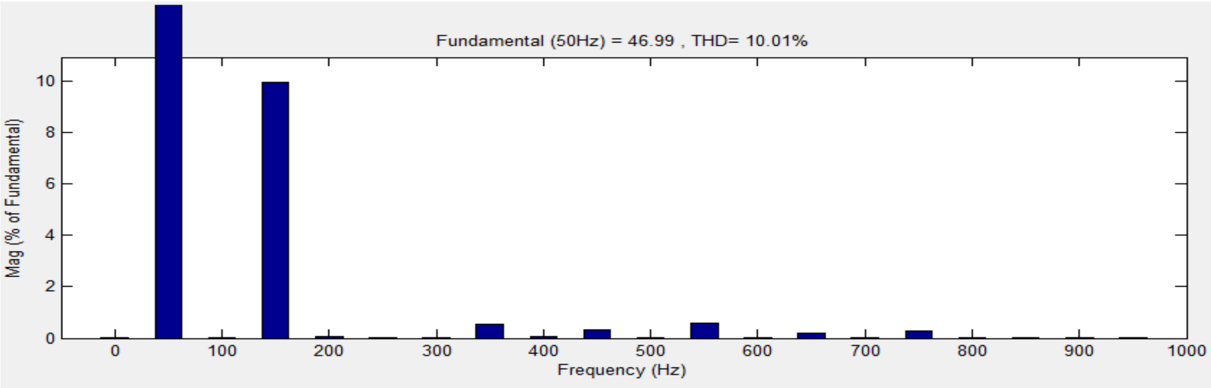
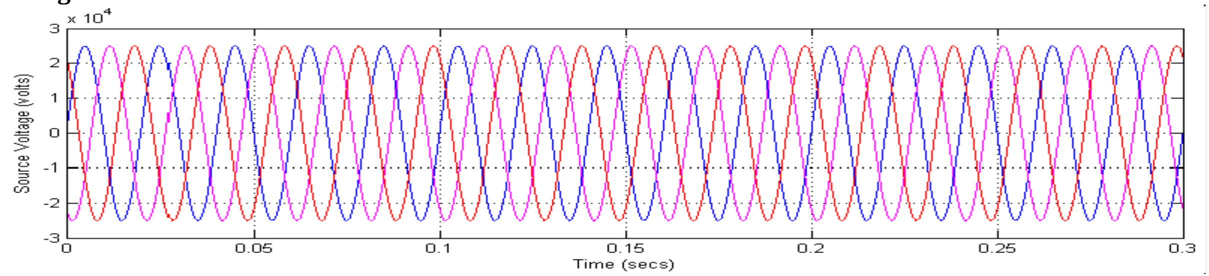


Figure 5.7: THD of compensated Source current using CHB converter

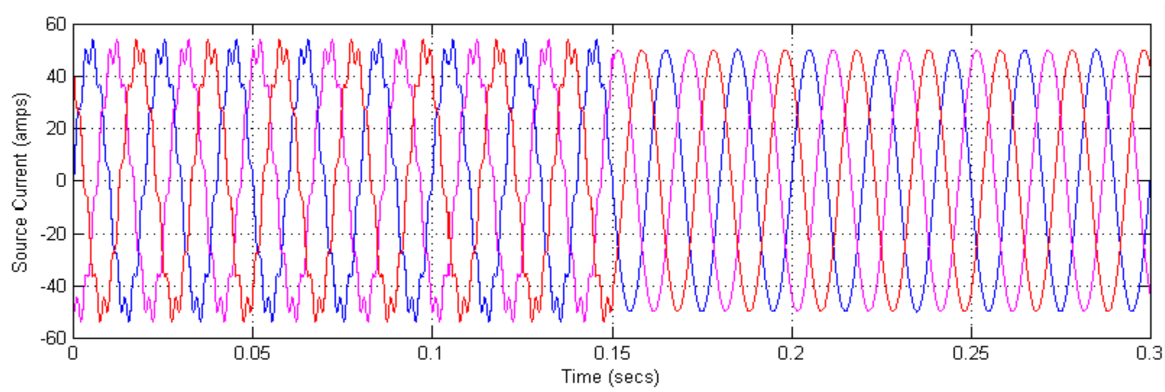
The waveform of the load current, source current, with non-linear load and their harmonic spectra are demonstrated in Figs. 5.6–5.7, respectively. The total harmonic distortion of the load current is 29.48%, and for the source current with SRF based control is 10.01%.

Performance of MMC based STATCOM with Non Linear Load for Compensation of source currents Source voltage



(a)

Source current



(b)

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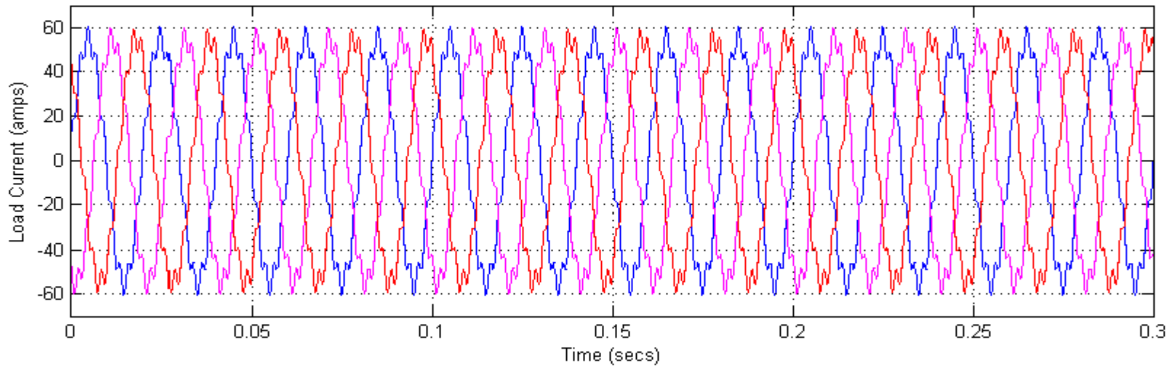
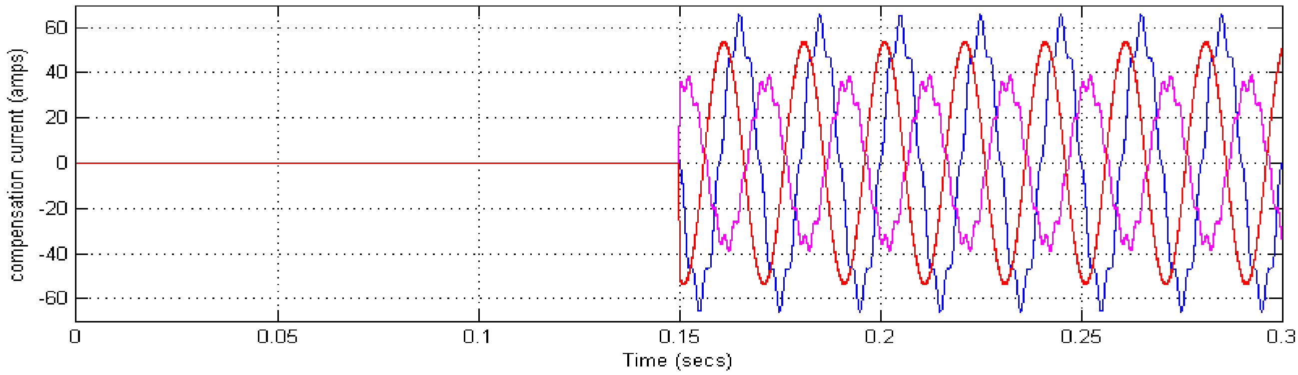
Load current



(c)

Compensated current



(d)

Fig.5.8. (a) Source voltage (b) Source current (c) Load current (d) Compensated current

The dynamic performance of the MMC based STATCOM with nonlinear and unbalanced load is given in Fig.5.8. It is observed that the harmonic current is compensated and the source currents are balanced and sinusoidal. The source current before compensation (time period (0- 0.15sec) and after compensation (time period 0.15- 0.3sec) is given in fig 5.8(b).

Performance of MMC based STATCOM with additional load (t=0.15sec) for Compensation of source current

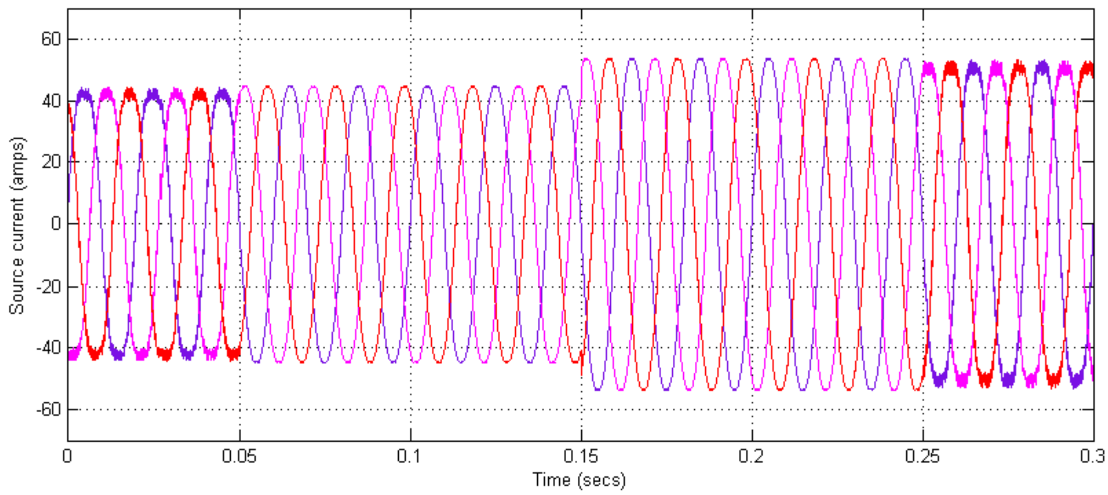


Figure: 5.9 compensated source current using MMC converter (additional Load)

Figure 5.9 shows an additional non linear load was connected at t=0.15 sec and disconnected at t=0.25 sec. The MMC based STATCOM is connected at t=0.05sec at this time the source current was compensated by statcom currents and reduces the harmonic component in source current.

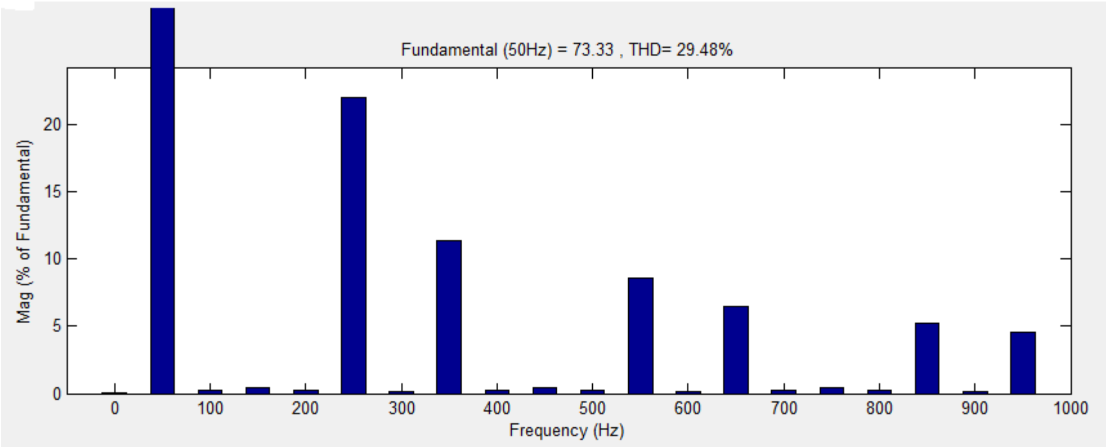


Figure: 5.10 THD of Load Current Spectra

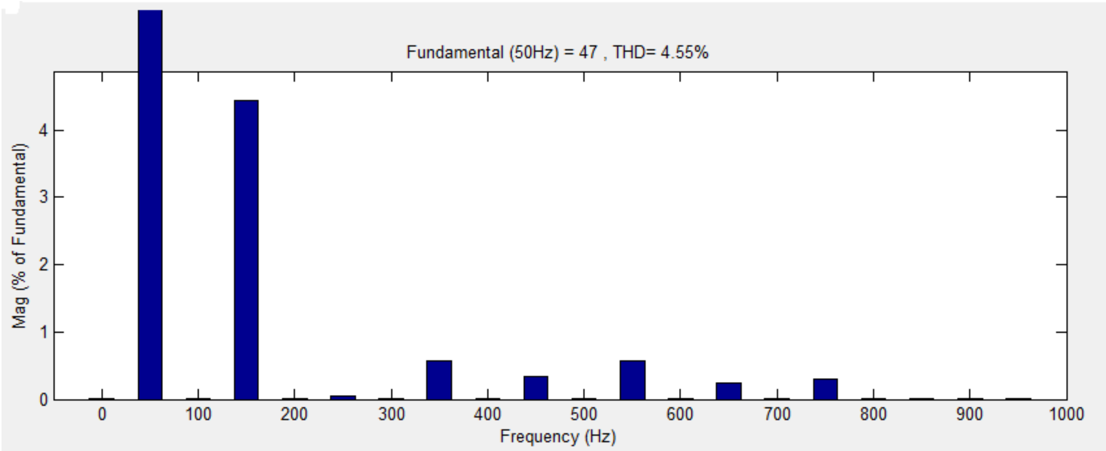


Figure: 5.11 THD of compensated source current using MMC converter

The waveform of the load current, source current, with non-linear load and their harmonic spectra are demonstrated in Figs. 5.10–5.11, respectively. The total harmonic distortion of the load current is 29.48%, and for the source current with SRF based control is 4.55%.

Table.5

Comparison of CHB based STATCOM with MMC based STATCOM method for Total Harmonic Distortion (THD) under non-linear loads.

Converter Model	Load current	Source current
SRF control based CHB converter	29.48%	10.01%
SRF control based MMC converter	29.48%	4.55%

6. CONCLUSION

The operation principle of a modular Multilevel Converter (MMC) was presented, describing the need for a correct balancing algorithm in order to have proper operation. A controller based on Synchronous Reference Frame Theory utilizes Park's Transformation in which quadrature axis and zero axis coordinates are made to

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zero, extracts only the average positive sequence component by means of Low Pass Filter (LPF) for mitigation of harmonics

Phase Shifted PWM technique is implemented to obtain the control pulses to three leg Modular Multilevel Converter (MMC). This PSPWM generates required pulses to compensate non linear and distorted load current to make the source end currents sinusoidal. The simulations are performed in MATLAB/Simulink environment to test the performances of the current control technique for CHB and MMC based STATCOMs. From the simulation results, it is observed that MMC based STATCOM makes the source end currents more sinusoidal compared to the CHB based STATCOM.

Appendix

Table 5.1: simulation parameters

Parameter	Value
Source Voltage(v_s)	25kV
Fundamental Frequency	50HZ
Line Resistance(R_s)	25mΩ
Line Inductance(L_s)	200µH
Interfacing Inductance(L_c)	5mH
Number of HBM in each leg(n)	4
DC link voltage of each HBM	3.3kV
DC link capacitance of each HBM	2.35mF
Switching/Sampling Frequency	1KHZ
Non-Linear Load	-

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