TELKOMNIKA Indonesian Journal of Electrical Engineering
Vol. 12, No. 9, September 2014, pp. 6622 ~ 6632
DOI: 10.11591/telkomnika.v12i9.5149

Simulation Research on Static and Dynamic Behavior of M-STATCOM

Riz.Jafri[1], Zha Xiaoming[1], S.Ali[2]
[1]High Voltage and Insulation Technology Institute,
School of Electrical Engineering, Wuhan University, Wuhan 430072, China
[2]Huazhong university of science and technology, college of Electrical and Electronic Engineering,
Wuhan, P.R. 430074, China
Corresponidng author, e-mail: kame7970@yahoo.com, xmzha@whu.edu.cn, 1441948925@qq.com

Abstract

In this paper, a novel static synchronous compensator/condensor based on the state-of-the-art modular multilevel converter called M-STATCOM is introduced. In order to support bus bar voltage, maintain the stability of DC-link capacitor voltage, obtain harmonics free output voltage and compensate reactive power under unbalanced operation, a novel direct current control (DCC) technique is proposed. For high accuracy and good control system response purpose Level-shift sine pulse width modulation (LS-PWM) technique is selected as the modulation strategy. The M-STATCOM is simulated in PSCAD/EMTDC environment and its static and dynamic responses are discussed. The effectiveness and feasibility of the proposed modulation and control strategy is validated by the simulation results.

Keywords*: M-STATCOM, LS-PWM modulation strategy, var generation, static and dynamic responses*

1. Introduction

Industry loads cause increasing power quality problems to the utility grids. Amongst many compensation techniques only static synchronous compensator (STATCOM) is found to provide precise and flexible control to mitigate disturbances and effectively improve power quality [1]. The multilevel converter based STATCOM easily reach up to medium or high-voltage high-power applications without transformers (as they are unreliable). The most commonly used multilevel converters are: Neutral point clamped (NPC), the flying capacitor (FC), modular multilevel converters (MMC). NPC and FC are discarded due to their drawbacks [2]. But the MMC is the next-generation multilevel converters so its operating performance, PWM scheme, experiment are examined in [3]. MMC provides a viable approach to construct a reliable and cost effective STATCOM (called M-STATCOM) with increased number of levels, capable of eliminating interface transformers and replace them by cheap reactors to allow active and reactive power exchange with the power system. The active power redistributes in the internal loops can be used for negative sequence balancing purpose [4]. Therefore, M-STATCOM can work continuously under the three-phase unbalance conditions, capable of surviving symmetrical and asymmetrical faults without increasing the risk of system collapse and it has fault management capability too.

The topology of M-STATCOM is explained in section two. Then, section three describes the Level-shift sine pulse width modulation (LS-PWM) technique as well as corresponding direct current control scheme, in section four M-STATCOM is simulated in PSCAD/EMTDC environment and its static and dynamic responses are discussed while the section five concluded out the paper.

2. Topology of M-STATCOM

Figure 1 demonstrates the topology structure of three phase MMC. In the converter, each phase consists of two legs that are names as positive leg and negative leg respectively. Each leg contains 50 identical, evenly and serially connected sub-modules (SMs) along with an inductor l (that limits fault current). Each sub-module consist of a floating dc capacitor C and two insulated-gate bipolar transistors (Tu and TL) that form a bi-directional chopper [5].

Received November 15, 2013; Revised May 10, 2014; Accepted June 5, 2014

The voltage of each capacitor is Vd/N (Vd is the voltage of the dc bus). In a sub-module, when the upper switch is on (lower switch is off), C is inserted in the circuit, in which the state of the sub-module is defined “on” or “1”; when the upper switch is off (lower switch is on), C is bypassed, here the sub-module is “off” or “0’. Then by controlling states of these sub-modules, the levels in the legs can be changed.The terminal voltage of each sub-module can be either its capacitor voltage or zero,depending on the switching states as shown in Table 1

Table 1. Switching States of the Sub-Module

Mode	Tu	TL	State
1	1	0	ON
2	0	1	OFF
3	0	0	BLOCK

Table 2. Switching States of Single Phase MMC

P+Q	P	Q	Lev Diff
2+2	2	2	0
2+1	2	1	-1
2	2	0	-2
2+1	1	2	1
2	1	1	0
2-1	1	0	-1
2	0	2	2
2-1	0	1	1
2-2	0	0	0

Tab.2 shows some possible states of a single phase MMC with fifty sub-modules per leg. Here P and Q are the numbers of the
“on”sub-modules in the positive and negative legs respectively.The output level is decided by the difference between voltages of the positive and negative legs and the load current.

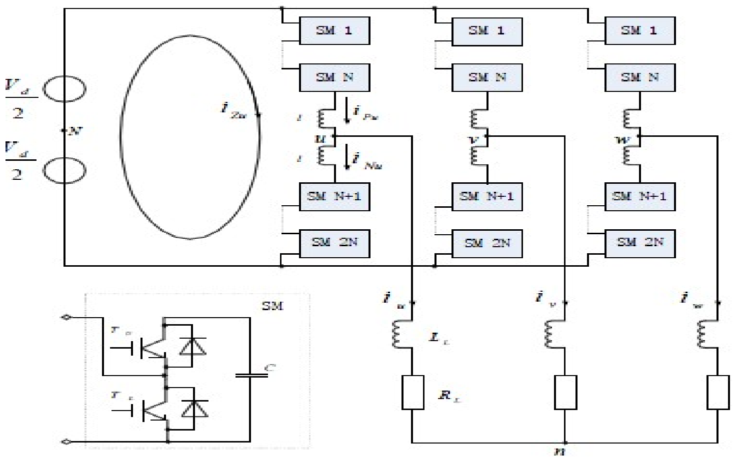


Figure 1. The Structure of Three-phase M-STATCOM along with Sub-Module

3. Modulation and Direct Current Control Techniques

MMC modulation strategy has a significant impact on the output voltage, harmonics, switching losses and capacitors’ voltage balancing. Multi-carrier-based PWM technique (multicarrier PWM modulation) is a common modulation method for multi-level converter. Multi-carrier modulation technique uses a reference or modulating signal (usually sinusoidal) which is compared and sampled through a number of carrier signal (usually triangular waves) as shown in Figure 2.

For high accuracy and good control system response purpose Level-shift sine pulse width modulation (LS-PWM)[6] technique is selected as the modulation strategy. It uses two reversed sine waves to compare with some triangular waves who has the same amplitude and phase but the vertical position shifts a level one by one, due to which the converter can work both in basic-level-mode and full-level-mode.

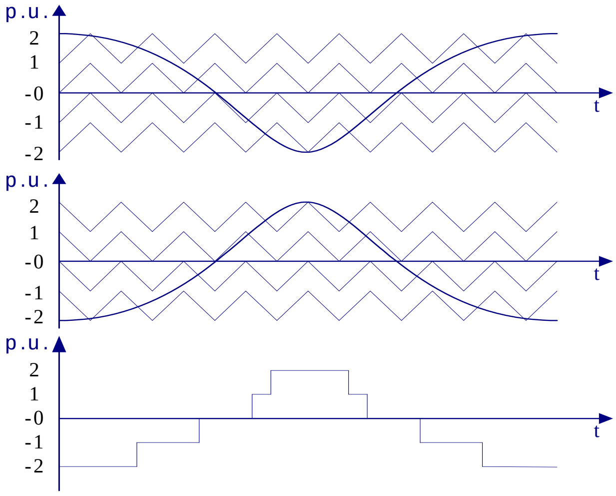
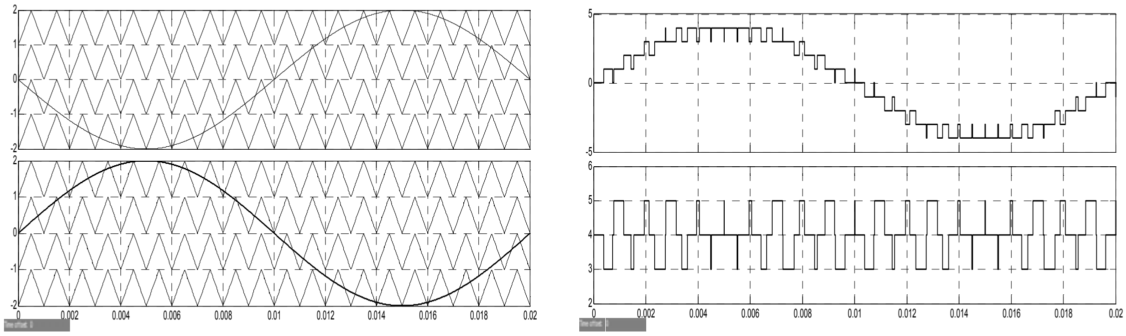
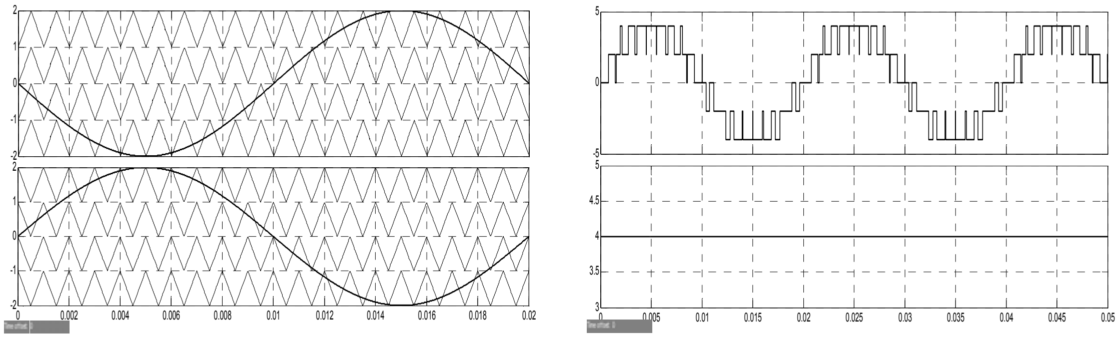


Figure 2. Multi-carrier PWM Modulation



(a) Basic level mode



(b) Full-level mode

Figure 3. Modulation Strategy for the MMC

For fastest and precise control, the direct current control compensation scheme[7] is selected.It is implemented by varying modulation index in order to get variation in output voltage of STATCOM while keeping capacitor voltage constant.

Applying KVL to Fig.1 the average of three-phase system mathematical model is:

$$\frac{1}{2}L\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{1}{2}R\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} u_{sa} \\ u_{sb} \\ u_{sc} \end{bmatrix} - \frac{1}{2}\begin{bmatrix} u_{ma} \\ u_{mb} \\ u_{mc} \end{bmatrix} \quad (1)$$

Where, u_{ma}~$_{mc}$ are the output voltage for phases a, b and c respectively. ia~c are M-STATCOM output currents for phases a, b and c respectively. By transferring the three phase grid-side voltages into the synchronous d-q coordinates as:

$$\begin{bmatrix} u_{sd} \\ u_{sq} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\omega t) & \cos(\omega t - \frac{2}{3}\Pi) & \cos(\omega t + \frac{2}{3}\Pi) \\ \sin(\omega t) & \sin(\omega t - \frac{2}{3}\Pi) & \sin(\omega t + \frac{2}{3}\Pi) \end{bmatrix} \begin{bmatrix} u_{sa} \\ u_{sb} \\ u_{sc} \end{bmatrix} = \begin{bmatrix} \sqrt{3}v \\ 0 \end{bmatrix} \quad (2)$$

Where, T is called the transformation matrix given by:

$$T = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\omega t) & \cos(\omega t - \frac{2}{3}\Pi) & \cos(\omega t + \frac{2}{3}\Pi) \\ \sin(\omega t) & \sin(\omega t - \frac{2}{3}\Pi) & \sin(\omega t + \frac{2}{3}\Pi) \end{bmatrix} \quad (3)$$

According to the definition of instantaneous reactive theory[8],the expressions of the instantaneous active and reactive powers in the dq coordinate system are as follows:

$$\begin{cases} P(t) = [U_{sd}(t) I_{sd}(t) + U_{sq}(t) I_{sq}(t)] = \sqrt{3} V i_d \\ Q(t) = [U_{sq}(t) I_{sd}(t) + U_{sd}(t) I_{sq}(t)] = \sqrt{3} V i_q \end{cases} \quad (4)$$

The instantaneous active power and reactive power exchange between the grid and M-STATCOM can be controlled by adjusting id and iq, separately. When id is positive, M-STATCOM absorbs active power and the corresponding capacitors are charged. If id is negative, M-STATCOM releases active power to the grid and the corresponding capacitors are discharged. The M-STATCOM releases leading reactive power when iq is positive, and lagging reactive power when iq is negative [9].

4. Simulation Study

4.1. Static Mode

To prove that the M-STATCOM, based on proposed control strategy, provides the desired compensation effects a three phase, M-STATCOM of Figure 1 is simulated in Matlab/Simulink environment. Simulation and loads' parameters are summarized in Table 3.

Table 3. Simulation and Load Parameters

Name	Symbol	Parameters
Active power	P	5MW
inductive reactive power	Q_L	5MVar.
Capacitive reactive power	Q_c	0
Load inductance	L_d	10mH
Load resistance	R_d	24Ω
DC capacitance	C	2.2nF
3-ph source voltage	V_{rms}	10kv
Carrier freq.	f_c	5kHz
Dc resistance	r_d	0.1Ω
Dc voltage	V_d	540v

In Figure 4, a single phase of voltage and current at the point of a power supply network are analyzed (in the time interval ranging from 0 to 0.1S) without the M-STATCOM action. Due to inductive load the current lags the voltage by 45°. The active power is 5MW while the inductive reactive power is 5MVar. The phase RMS volage is 5.3kv while the phase RMS current is 412A. Due to the large inductive reactive power, the loss of line voltage is large and the load-side voltage drop is also obvious (5% of the rated voltage), hence the power quality is also poor. Thus, in order to improve the voltage level the enough capacitive reactive power must be given to the system through M-STATCOM action.

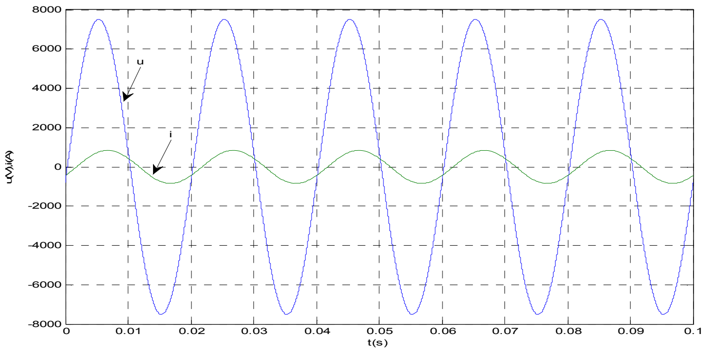


Figure 4. A Single Phase of Voltage and Current without the M-STACOM Action

In Figure 5, M-STATCOM action is shown and a single phase of voltage and current at PCC are analysed. As soon as, the M-STATCOM is put into operation, the phase RMS voltage is increased to 5.8kV while the phase RMS current is reduced to 346A. It is also evident from the Figure 5 that the current and voltage are in phase. The load have become almost resistive because M-STATCOM generated the capacitive reactive power in order to compensate the inductive reactive power. Thus, M-STATCOM improved the power factor.

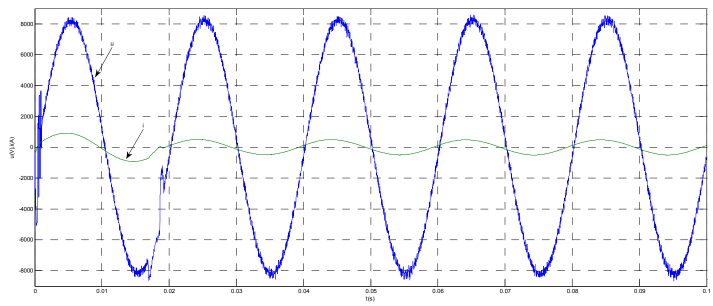
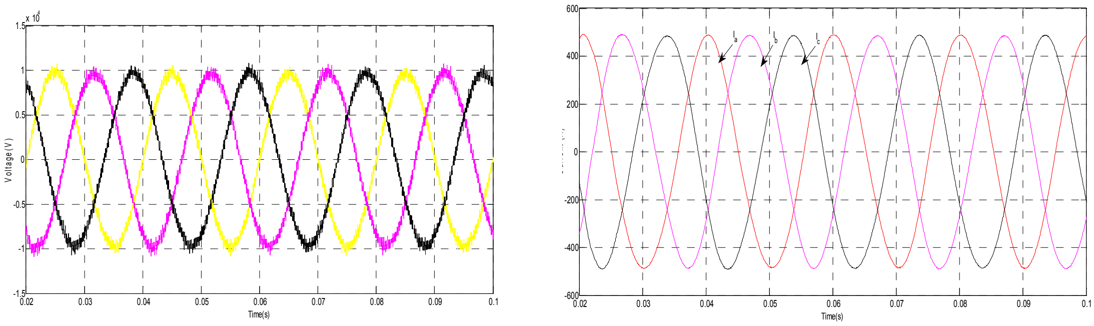


Figure 5. A Single Phase of Voltage and Current at PCC with M-STATCOM Action

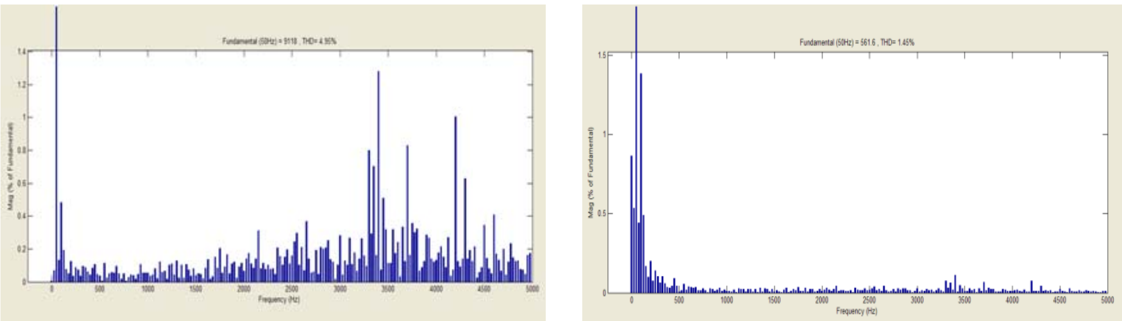
Figure 6(a-b) shows the M-STATCOM output voltage and current waveforms respectively. Both the output voltage and current waveforms have better quality because they have reached sinwave approximation with least THDs. The M-STATCOM output voltage although greater in amplitude with the grid voltage but both are in phase. As the M-STATCOM is in capacitive mode hence its current leads the grid voltage. However, the M-STATCOM output current doest not lead the grid voltage by 90°because there are some losses of M-STATCOM and active current.



(a) M-STATCOM output voltage (b) M-STATCOM output current

Figure 6. M-STATCOM Output Voltage and Current

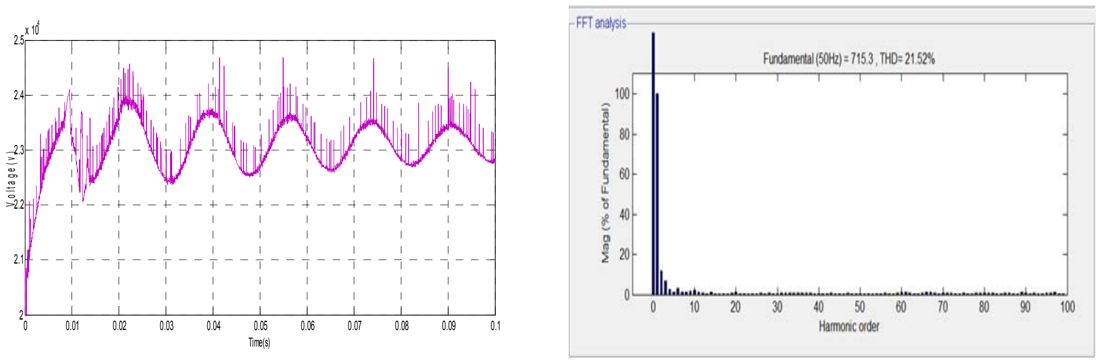
The FFT analysis of M-STATCOM output voltage and current are shown in Figure 7(a-b) respectively.The output voltage has higher harmonics (THD=4.95%) as compare to the harmonic contents of the output current (THD=1.45%) because the connected impedance filters the most of the harmonics. So, any other filter is not necessary thus it is cost saving.



(a) Voltage (b) Current

Figure 7. M-STATCOM output voltage and current harmonic contents

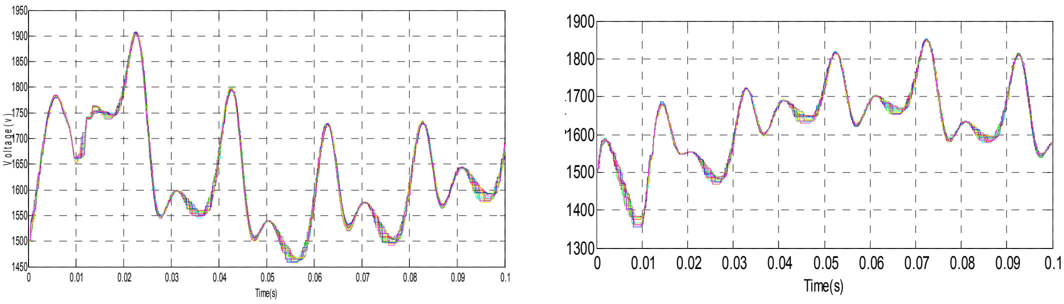
M-STATCOM DC bus voltage and its FFT analysis shown in Figure 8. As can be seen from Figure 8(a), the DC bus voltage fluctuation is small and has the double frequency viz. 100HZ harmonic waves, with least harmonic components (THD=47.94%).This proves that the DC bus voltage regulator control strategy is good.



(a) M-STATCOM DC bus voltage (b)FFT analyses of M-STATCOM DC bus voltage

Figure 8. M-STATCOM DC Bus Voltage and Harmonic Content

The M-STATCOM'S capacitor modules voltages for upper and lower bridges are shown in Figure 9. As it can be seen from Figure 9 that the 14 capacitors' voltage fluctuations both for lower and upper arm are same and of very small value around 0.1%.Thus,it verifies that the capacitance voltage control strategy is successful.



(a) Upper bridge arm Vc1~14 (b) Lower bridge arm Vc15~28

Figure 9. M-STATCOM Capacitors' Voltages for Upper and Lower Leg

4.2. Dynamic Mode

Nowadays mostly city grid are constructed by the underground cables instead of overhead lines. The underground cables' capacitance to earthis higher than the overhead one.
The Ferranti effect [10] (an increase in voltage occurring at the receiving end of a long transmission line, to the voltage at the sending end, when load is light or the load is disconnected) is much more pronounced in underground cables, even in short lengths, because of their high capacitance.

That's why M-STATCOM is used. In order to verify the M-STATCOM dynamic compensation effect, the load is set variable.The load active power constant equals to 5MW while the load reactive power Q varies from +5MVar to -5MVar at 0.1s.The simulation parameters are shown in Table 4.

Table 4. M-STATCOM's Simulation Parameters

Name	Symbols	Parameters
3-phase source voltage	V_{rms}	10kv
DC power supply	V_{dc}	22.7kV
Active power	P	5MW
inductive reactive power	Q_L	5MVar
Capacitive reactive power	Q_c	-5Mvar
Dc capacitance	C	4.7nF
Dc capacitance	Zs_a	70Ω+10mH
Operating Frequency	f	50Hz
Triangular carrier frequency	f_c	5kHz
DC equivalent resistance	R_{dc}	0.5Ω

In Figure 9, in the time period from 0 to 0.2 S, a single phase of voltage and current at the Point of Common Coupling (PCC) are analyzed before and after 0.1s, without the M-STATCOM action. There are two modes: Inductive mode range is from 0 to before 0.1S and capacitive mode range starts from 0.1S to 0.2S. Before 0.1s, in inductive mode, the current lags the voltage by a certain angle. Besides this there is large inductive reactive power and high voltage drop. These factors made power quality poor. As the load is variable so after 0.1s,in the capacitive mode, the current leads the voltage by a certain angle. Due to excessive capacitive reactive power, voltage rises 5% higher than the rated voltage, which is also unwanted situation. So, in both the cases for the stable and efficient grid operation M-STATCOM is absolutely necessary.

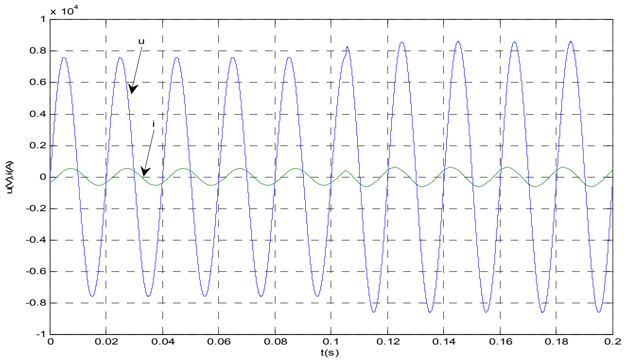


Figure 9. A Single Phase of Voltage and Current without the M-STACOM Action

In Figure 10, a single phase of voltage and current at PCC with M-STATCOM action is shown. As can be seen from the Figure 10 that after the M-STATCOM is put into operation, either before or after the 0.1s, current and voltage are substantially in phase and the load became equivalent to a resistive load. Before 0.1s, M-STATCOM operated in the capacitive mode. It generated capacitive reactive power, reduced the inductive current flowing through the lines, reduced line losses, improved the voltage regulation at the load side and hence provided a high power factor. After 0.1s, M-STATCOM operated in the inductive mode so it absorbed inductive reactive power of the charging power cable, reduced line losses, reduces the voltage regulation at PCC and hence improved the power factor.

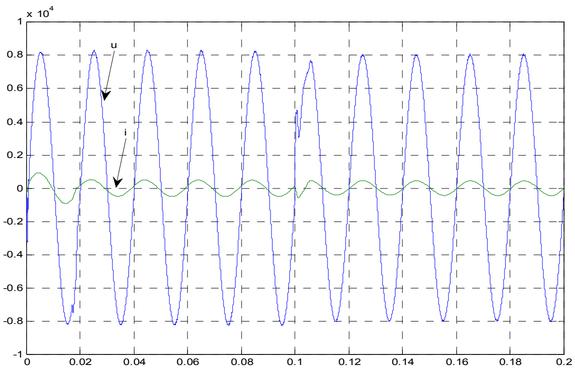
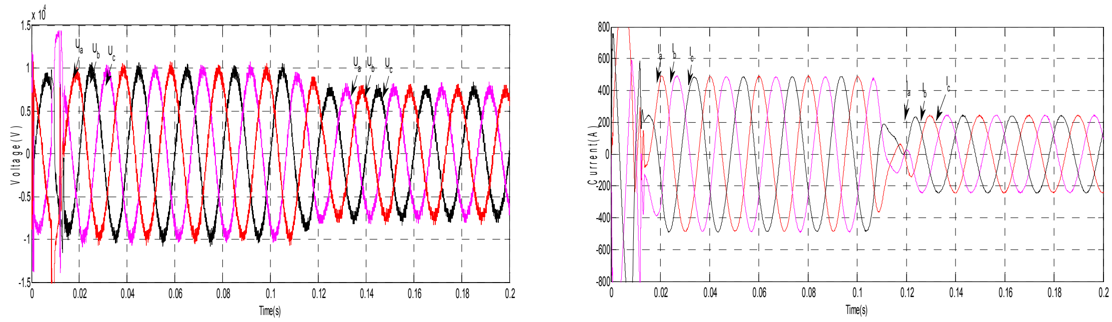


Figure 10. A Single Phase of Voltage and Current at PCC with M-STATCOM Action

Figure 11(a-b) shows the M-STATCOM 3-phase output voltage and current respectively. Before the 0.1s, the M-STATCOM detected inductive load, the M-STATCOM output voltage (Vc=1kv) is greater than the grid voltage (Vl=0.8kv) while after 0.1s the M-STATCOM detected capacitve load, now the M-STATCOM output voltage (Vc=0.8kv) is less than the grid voltage (Vl=1kv). Therefore, whether the load is inductive or capacitive the proposed reactive current detection techniques can correctly sense nature of the load and then calculates the required quantity of the compensation current (either capacitive or inductive).



(a) 3-phase M-STATCOM output voltage (b) 3-phase M-STATCOM output current

Figure 11. 3-phase M-STATCOM Output Voltage and Current

Figure 12 depicts that by using direct current control technique, the output current is in good track with the command current, the resulting error is so small that it can be negligible. Hence fastest response is obtained.

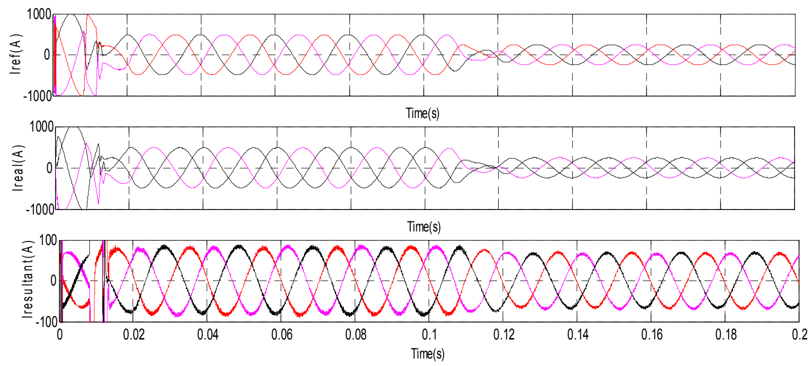


Figure 12. Direct Current Control Strategy

In Figure 13 M-STATCOM's capacitor voltages for upper and lower bridge arm are shown respectively. As can be seen from Figure 10 that voltage fluctuations of upper arm's 14 capacitors is in good track and similar with the lower arm's 14 capacitors and upper arm. This illustrates that the proposed capacitance voltage balancing algorithm can achieves the desired purpose.

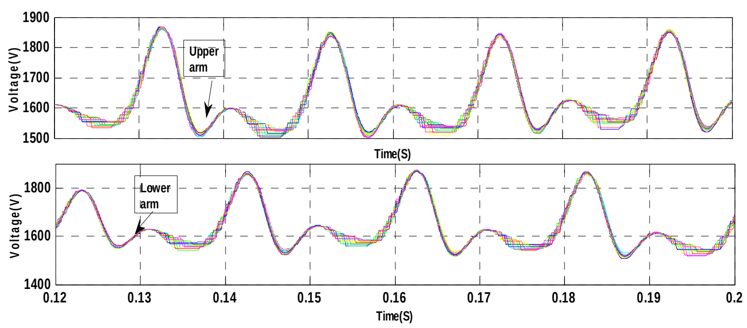


Figure 13. M-STATCOM Capacitor Voltage Upper and Lower Leg

In Figure 14 M-STATCOM DC bus voltage is shown. As can be seen from Figure14, the DC bus voltage fluctuation is small with least harmonic components.

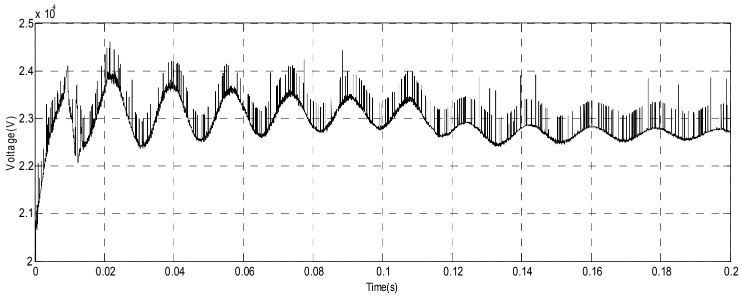


Figure 14. M-STATCOM DC Bus Voltage

In Figure 15, the real power P is provided in both the modes (inductive and capacitive). The difference is that before 0.1s (inductive mode) P is provided more about 0.5MW and after 0.1s P is provided less i.e about half of the inductive mode power 0.25MW. Similarly reactive power Q is provided in both the modes (inductive and capacitive). In inductive mode Q=-4.9MVAr are given to the system while after 0.1s that is capacitive mode Q=+3.9Mvar are absorbed from the system.

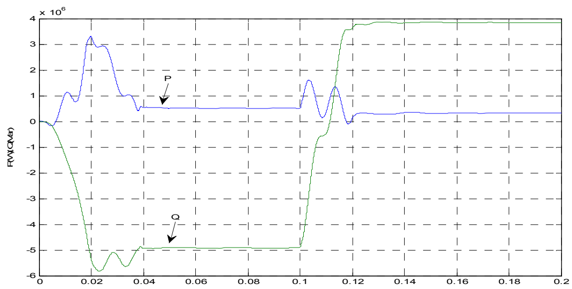


Figure 15. M-STATCOM's Consumption of Active Power and Reactive Power

5. Conclusion

The computer simulation in the PSCAD/EMTDC environment confirmed the proper operation of the three-phase M-STATCOM.Direct current control(DCC) strategy along with LS-PWM validates a quick response method with especial context to the following points:

1) Voltage sag mitigation.
2) Reactive power compensation in inductive as well as capacitive mode.
3) maintain the stability of DC-link capacitor voltage
4) The line losses ,voltage drops and Harmonic cancellation, and
5) Simultaneous load balancing procedure, while controlling and balancing all of the DC mean voltages even during the transient states, etc.

References

[1] Acha E. A New STATCOM Model for Power Flows Using the Newton–Raphson Method Power Systems. *IEEE Transactions on Power Electronics*. 2013; 28(3): 2455-2465.
[2] Rédha CHIBANI, ElMadjid BERKOUK, Mohamed Seghir, BOUCHERIT. Study of a new DC voltage equalising circuit for Five-Level Neutral Point Clamped-Voltage Source Inverter. *Journal of Electrical Systems*. 2011; 7-2: 131-148
[3] S Rohner, S Bernet, Modulation, Losses. Semiconductor Requirements of Modular Multilevel Converters. *IEEE transactions on industrial electronics*. 2010; 57(8): 2633-2642.

[4] K Jafri, CHEN Baichao, CHEN Yaojun, et al. Modeling, Simulation and Control Strategy of a Novel 10kV 15-level M-STATCOM under SVG condition. *Journal of High Voltage Engineering*. 2013; 39(5): 1246-1251.
[5] Casadei G, Teodorescu R, Vlad C, et al. *Analysis of dynamic behavior of Modular Multilevel Converters: Modeling and control.* 16th International Conference on System Theory, Control and Computing (ICSTCC), Sinaia. 2012: 1-6.
[6] Lennart Angquist, Antonios Antonopou-los, Daniel Siemaszko, et al. Open-Loop Control of Modular Multilevel Converters Using Estimation of Stored Energy. *IEEE Transactions on Industry applications*. 2011; 47(6): 2516~2524.
[7] Carrasco J, Galvan E, Perales M, et al. *Direct current control: A novel control strategy for harmonic and reactive compensation with active filters under unbalanced operation*. The 27th Annual Conference of the IEEE Industrial Electronics Society. IECON '01, Denver, Colorado. 2001: 1138-1143.
[8] Akagi H, Watanabe HE, Aredes M. Instantaneos power theory and applications to power conditioning. New Jersey, Canada: John Wiley & Sons, 2007.
[9] K Jafri, CHEN Baichao, CHEN Yaojun, et al. *Direct current control and experiment of a novel 9-level modular multilevel converter*. IET International Conference on Information Science and Control Engineering (ICISCE 2012), Shenzhen, China: 2012:1526-1530.
[10] Ferranti effect (Wikepedia). (2013-4). http://en.wikipedia.org/wiki/Ferranti_effect