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MMC based D-STATCOM for Different Loading Conditions

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***Abstract*— In present day distribution systems, major power consumption has been in reactive loads, such as fans, pumps etc. These loads draw lagging power-factor currents and therefore give rise to reactive power burden in the distribution system. Moreover, situation worsens in the presence of unbalanced loads. Excessive reactive power demand increases feeder losses and reduces active power flow capability of the distribution system, whereas unbalancing affects the operation of transformers and generators. A Distribution Static Compensator (DSTATCOM) can be used for compensation of reactive power and unbalance loading in the distribution system. Many efforts have been done to realize it without bulky and heavy coupling transformer and to reduce the size of bulky inductive filters, using multilevel converters. Multilevel converters are divided to three categories: neutral point clamped (NPC), flying capacitor (FC) and cascaded H-bridge (CHB) converters. Among the mentioned topologies, the cascaded H-bridge converter is more interested due to its extreme modularity, easier dc voltage balancing, and minimum number of required components for a specific number of voltage levels. However, both star-type and delta type cascaded H-bridge converters have the limitations under the situation of unbalanced load or asymmetrical power supply. In this project, a new control strategy with a focus on dc-link voltage control of splitting capacitors is proposed, along with the theoretical analysis and associated discussions. The proposed concept is tested at different loading conditions by using Matlab/Simulink software and the corresponding results are presented.**

***Index Terms*— Neutral point clamped (NPC), DSTATCOM, cascaded H-bridge converters, flying capacitor (FC) and Modular Multilevel Converters**

I. INTRODUCTION

The typical structure of a MMC is shown in Fig. 1, and the configuration of a Sub-Module (SM) is given in Fig. 2. 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[1].

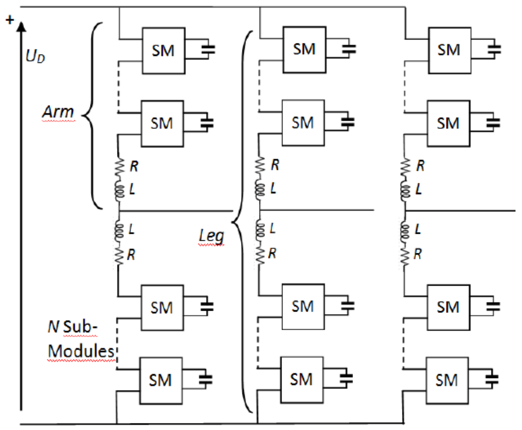

Figure 1 - Schematic of a three-phase Modular Multi-level Converter

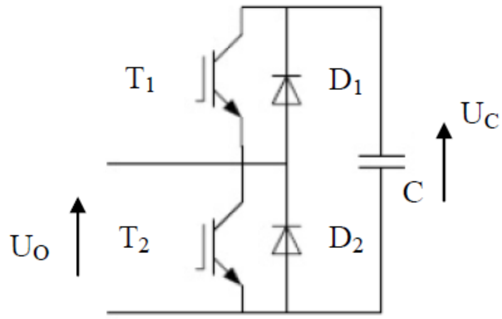

Fig.2 Chopper cell of a Sub-Module

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.

The cascaded single-phase H-bridge converter has been regarded as the preferable alternative for MVD STATCOM applications because of natural modular, high reliability, and unlimited voltage levels [5], [6]. However, both star-type and delta type cascaded H-bridge converters have the limitations under the situation of unbalanced load or asymmetrical power supply. A star-type cascaded H-bridge converter applying for unbalanced load compensation requires a large dc voltage margin for zero-sequence voltage, which is not acceptable in MV applications [7]. A delta-type cascaded H-bridge converter cannot sufficiently compensate for reactive power and unbalanced load under a serious asymmetrical grid fault, because the redistribution of active power among three phases caused by negative-sequence source voltage also requires a

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large zero-sequence current to create a counterpart for cancellation [8]. 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

II. CONTROL STRATEGY

Recently, the modular multilevel converter (MMC) gains much attention by researchers and engineers because of its more degrees of freedom for control and its high-power applications.

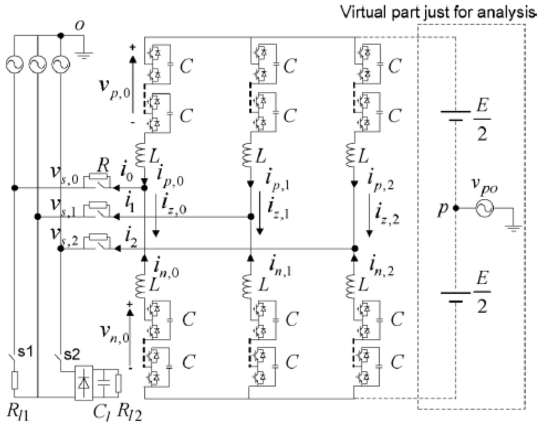


Fig.3 Circuit configuration for MMC-based D-STATCOM

However, MMC is companied with the issue of splitting capacitor voltage control. Reference presents an MMC-based STATCOM system, but the dc voltage balancing control has not been sufficiently discussed. The so-called "sorting voltage of capacitor," which decides the charge or discharge of each sub module by current direction and dc-link voltage value, can efficiently balance the individual dc voltage of chopper cells, but the balancing between the upper leg and lower leg of each phase pair is not clear. Moreover, the control strategy employing circulating current for dc voltage control cannot be directly applied to three-phase three-wire MMC-based D-STATCOM, because the three independent fundamental components in circulating current for dc voltage balancing of upper and lower legs may not cancel out all the time to comply with KCL law

The control strategy is composed by three parts: decoupled compensating current control, circulating current control, and dc voltage control. The details of dc voltage control are presented in the next section.

A. Decoupled Compensating Current Control

Referring to Fig. 3, the ac voltages of the upper and lower leg in one phase could be written as

$$v_{p,m} = E/2 - v_m - v_{z,m}/2$$
$$v_{n,m} = E/2 + v_m - v_{z,m}/2 \qquad (1)$$

where and are the components to produce compensating current and circulating current, respectively. According to (1), the relationship between compensating current and ac output voltage are obtained by

$$2v_{s,m} + L\frac{di_m}{dt} + R \cdot i_m - 2v_m - 2v_{po} = 0 \qquad (2)$$

The zero-sequence current does not exist in a three-phase three-wire power system. The zero-sequence components in source voltage and converter ac voltage do not affect the output current of the converter, so the third equation in (3) should be neglected. When taking positive-sequence and negative- sequence components into account and introducing two proportional and integral (PI) regulators with parameters of and for close-loop current control,

$$v_{sd} + \frac{L}{2}\frac{di_d}{dt} + \frac{R}{2}\cdot i_d + \frac{\omega L}{2}\cdot i_q - v_d = 0$$
$$v_{sq} + \frac{L}{2}\frac{di_q}{dt} + \frac{R}{2}\cdot i_q - \frac{\omega L}{2}\cdot i_d - v_q = 0$$
$$v_{s0} + \frac{L}{2}\frac{di_0}{dt} + \frac{R}{2}\cdot i_0 - v_{po} = 0 \qquad (3)$$

B. Circulating Current Control

The difference between two equations reveals a relationship between circulating current and ac output voltage

$$2L\frac{di_{z,m}}{dt} + 2R\cdot i_{z,m} + v_{z,m} = 0 \qquad (4)$$

The command voltage for producing circulating current is obtained by introducing a proportional regulator with the parameter

$$v^*_{z,m} = k_{\text{zip}}\left(i^*_{z,m} - i_{z,m}\right) \qquad (5)$$

Here, is the command circulating current, which is calculated by the dc voltage-control algorithm. Substituting and into (1), the command voltages for two legs in one phase are obtained. When considering the individual control with trims of for ac voltage, the command voltage for each chopper cell is given by

$$v^*_{p,mj} = \frac{E}{2N} - \frac{v^*_m}{N} - \frac{v^*_{z,m}}{2N} + \Delta v^*_{p,mj}$$
$$v^*_{n,mj} = \frac{E}{2N} + \frac{v^*_m}{N} - \frac{v^*_{z,m}}{2N} + \Delta v^*_{n,mj}$$
$$(j = 1, 2 \ldots N) \qquad (6)$$

Where N is the cascaded number for each leg

III. POWER-FLOW CALCULATION

Fig. 3 shows the configuration of the MMC circuit with the defined positive directions. Under unbalanced conditions, source voltage and compensating current contain positive-sequence and negative-sequence components. In order to improve dc bus voltage utilization, the injection of common third-harmonic voltage is considered. The circulating current contains dc and ac components. The relating equations are expressed as

$$v_{s,m} = U_P \sin(\omega t - m\cdot 2\pi/3)$$
$$+ U_N \sin(\omega t + \theta + m\cdot 2\pi/3) \qquad (7)$$

$$i_m = I_P \sin(\omega t + \alpha - m \cdot 2\pi/3) + I_N \sin(\omega t + \beta + m \cdot 2\pi/3) \quad (8)$$

$$v_{po} = -U_P \sin(3\omega t)/6 \quad (9)$$

$$i_{z,m} = I_{z,m} + I_{1th} \cdot v_{s,m} + I_{3th,m} \sin(3\omega t) \quad (10)$$

where m= 0,1,2 represent the ,a b, and c phase, respectively. Up and U_N are amplitudes of positive-sequence and negative-sequence components in the source voltage. I_P and I_N are those of the compensating current, respectively. The original phase angles are the dc component of circulating current, and are the coefficient of fundamental current; is the amplitude of the third-harmonic component. The sum of and the sum of must be zero to satisfy the KCL law. According to KVL law, the set of voltage-current equations for the upper and lower legs in one phase is obtained

$$v_{p,m} = -v_{s,m} - L\frac{di_{p,m}}{dt} - R \cdot i_{p,m} + \frac{E}{2} + v_{po}$$
$$v_{n,m} = v_{s,m} + L\frac{di_{n,m}}{dt} + R \cdot i_{n,m} + \frac{E}{2} - v_{po} \quad (11)$$

It is necessary to make an important remark: the equations wrote and discussed in previous section lead to a continuous model, suitable for analysis and understanding of operation principle of the MMC. On the other hand, from the control point of view, these equations are not easy to use: even if it is possible to decouple continuous and alternate component of differential current, in order to properly track references, non-linear couplings make really complex advanced control structures. The control strategy implemented is a linear control which aims to operate in the proximity of the region where the control can be considered linear: actually, control input will be limited in order to preserve this assumption. Otherwise, the non-linear input of the control can affect operation of the system, leading to instability.

Two different loops will be implemented, the first one to control the overall energy of the MMC leg, the second to control the balance between upper and lower arms of the phase-leg. The interaction between two loops may lead to instability: because of the non-linear configuration of system equations, it is hard to analyze systems coupling properly (for instance Relative Gain Array analysis). It is however evident that total energy and energy balance interact dynamically in system operation: in order to make a decoupling, balance of energy loop is tuned in order to be greatly slower than the overall energy loop. This frequency decoupling will highly benefit differential current waveform: if not performed, overall energy and balance interaction leads to a really distorted differential current. This current, flowing in the phase-leg, would produce a voltage drop on the phase impedance, increasing losses and disturbances in the stability of the system.

Limitations

This thesis main objective is to find a performing control system for the energy stored in the converter: even if MMC is a well-known topology of converter, few modeling and control approach are available. To carry out this primary analysis, a modeling approach has been chosen and followed, and can be found in [8]: this approach showed to be the most promising, both for the analysis of MMC operation and for the development of control structure. However, in Chapter V of this thesis a new modeling approach is suggested, in order to simplify control strategy study. Being the energy monitoring and control the aim of this project, modeling neglects low level operation and dynamics of the system: sub-modules are simplified with an equivalent variable voltage source, ideally controlled. This assumption, gives the opportunity to study the system from a proper point of view in terms of energy: on the other side, sub-modules operation is hidden and all issues connected are not dealt in this thesis. A different approach should be investigated, in order to account also sub-modules operation in the modeling and through this, in control strategy development.

IV. SIMULATION RESULTS

Here the simulation carried by different cases 1) DC voltage control for chopper-cell-based MMCs 2) Linear balanced condition 3) linear unbalanced condition 4) Non-linear balanced condition 5) Non-linear unbalanced condition

Case-1 DC voltage control for chopper-cell-based MMCs

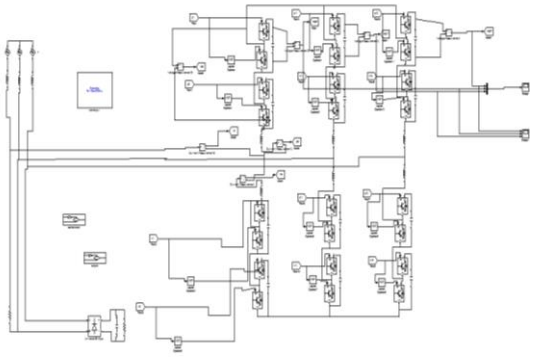


Fig.4 Matlab/simulink model of DC voltage control for chopper-cell-based MMCs

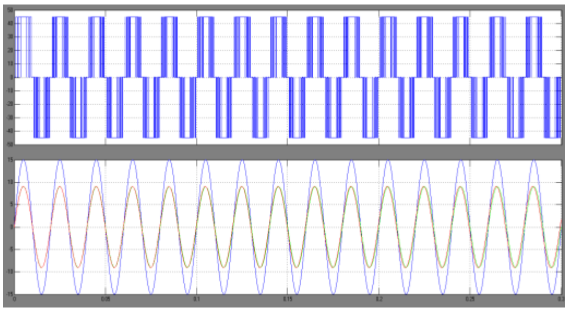


Fig.5 simulation waveforms of the ac-side voltage and current

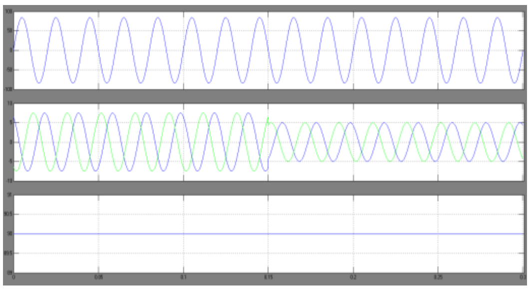


Fig.6 overall voltage control with a dc-link voltage feed forward control

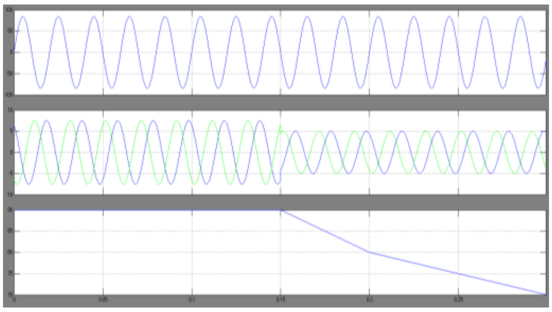


Fig.7 Without feed forward control.

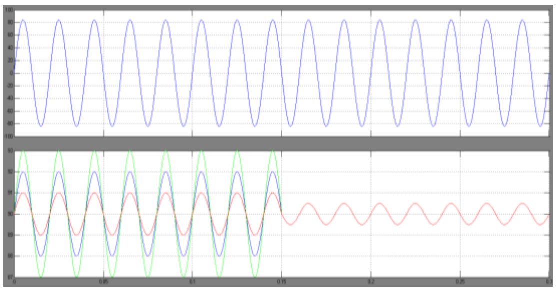


Fig.8 overall voltage control, leg balancing control, and individual voltage control

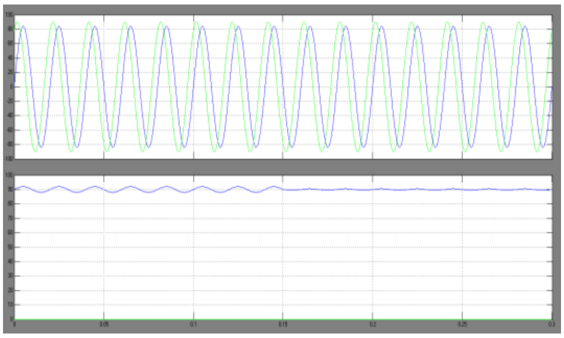


Fig.9 phase balancing control and individual voltage control

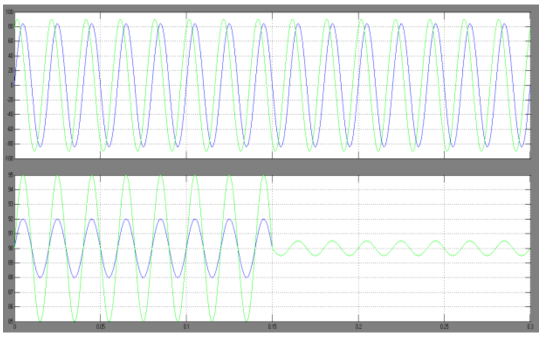


Fig.10 phase balancing control, and leg balancing control.

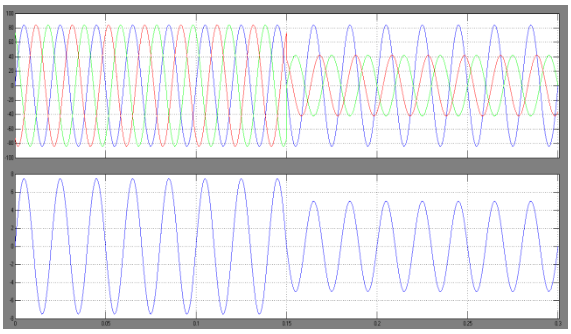


Fig.11 performance of compensating unbalanced and distorted load when an asymmetrical grid fault occurs, Source voltage and A-phase source-end current

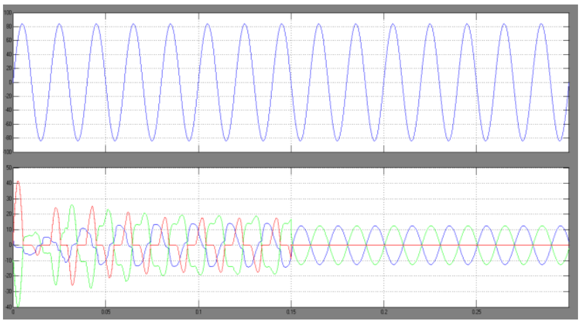


Fig.12 A-phase source voltage and load current

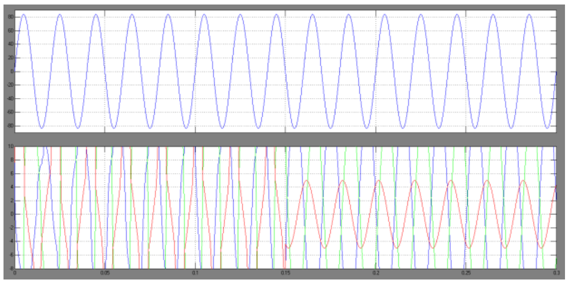


Fig.13 A-phase source voltage and D-STATCOM compensating current

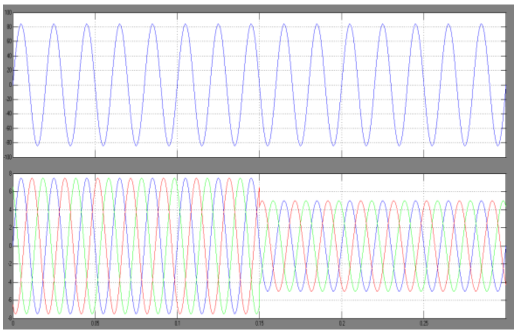


Fig.14 A-phase source voltage and source-end current after compensation

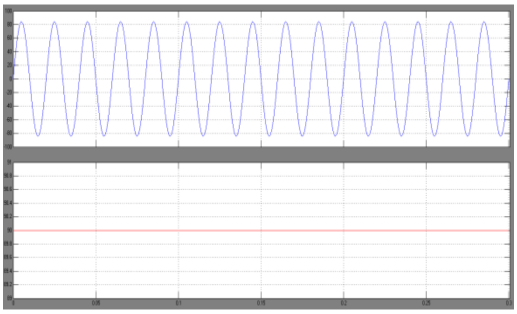


Fig.15 A-phase source voltage and dc capacitor voltages.

Case-2 Linear balanced condition

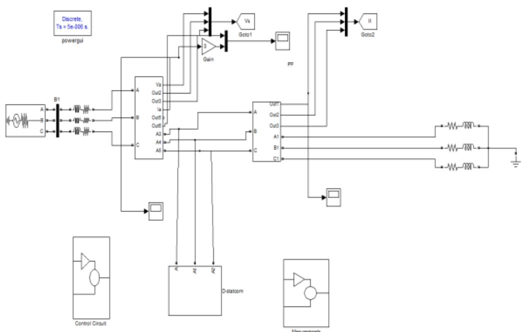
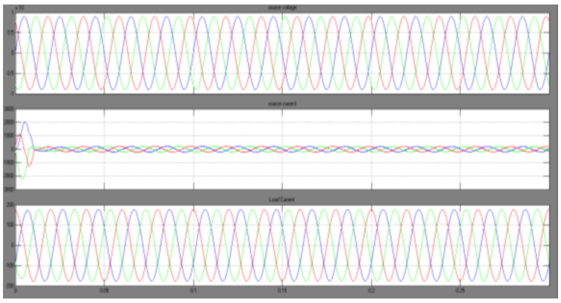


Fig.16 Matlab/simulink model of different loading condition



Linear balanced condition Source voltage, source current and load current

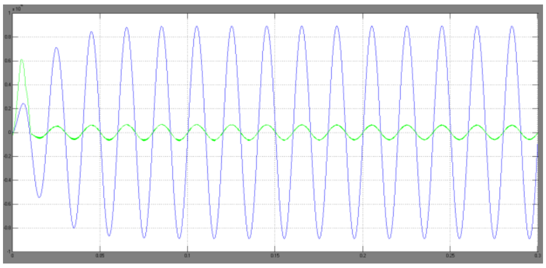


Fig.9 shows the Power Factor of Proposed Balanced Linear Load Condition.

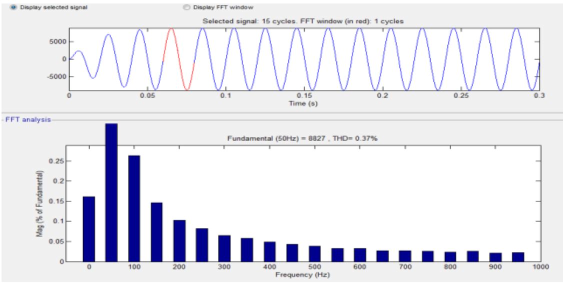
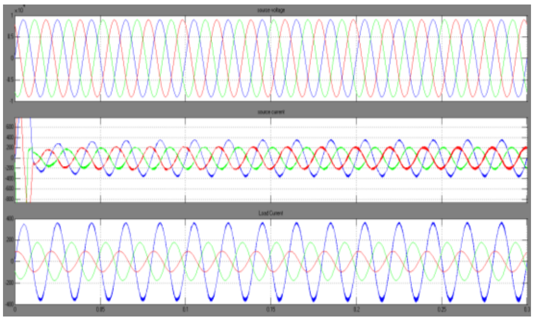


Fig.14 FFT Analysis of Source Current of Proposed balanced Linear Load Condition

Case-3 linear unbalanced condition



Linear unbalanced condition Source voltage, source current and load current

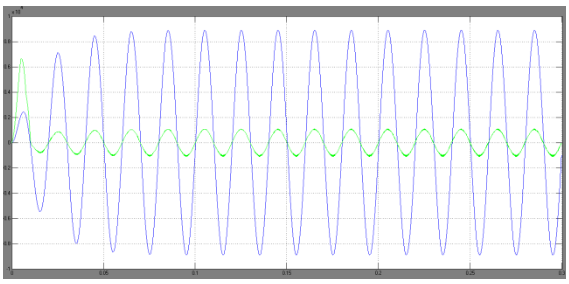


Fig.9 shows the Power Factor of Proposed Un-Balanced Linear Load Condition.

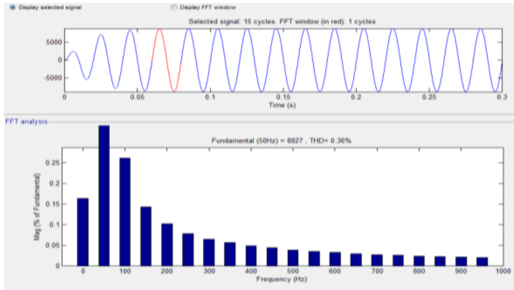
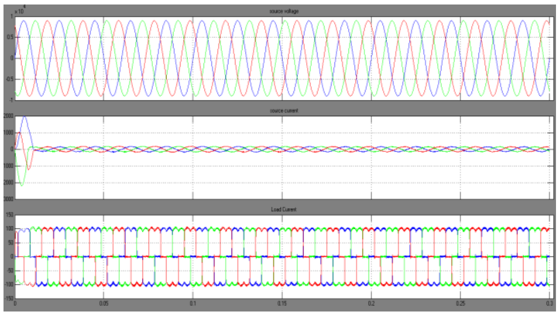


Fig.14 FFT Analysis of Source Current of Proposed unbalanced Linear Load Condition

Case-4 Non-linear balanced condition



Non-linear balanced condition Source voltage, source current and load current

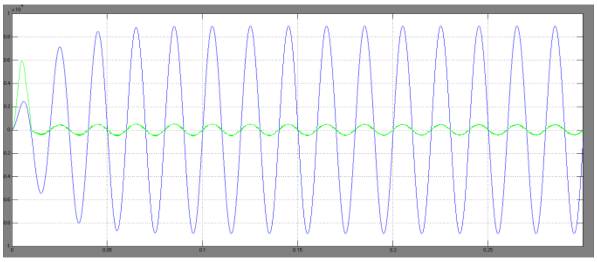


Fig.9 shows the Power Factor of Proposed Balanced Non-Linear Load Condition.

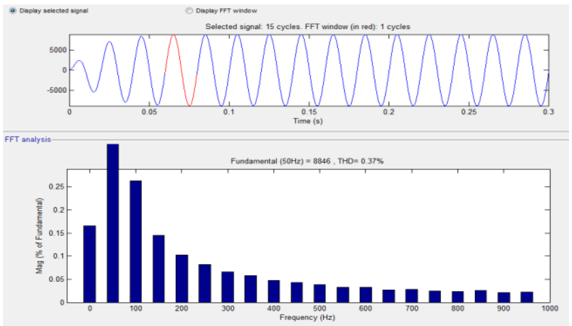
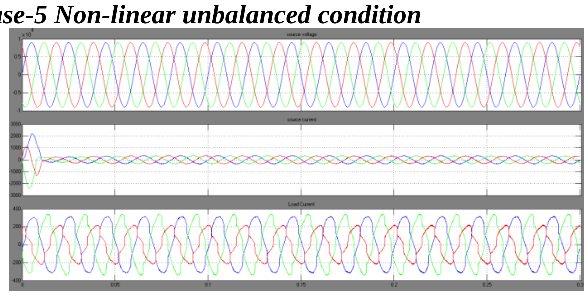


Fig.14 FFT Analysis of Source Current of Proposed balanced Non Linear Load Condition

Case-5 Non-linear unbalanced condition



Non-linear unbalanced condition Source voltage, source current and load current

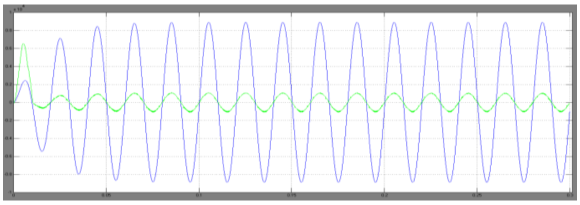


Fig.9 shows the Power Factor of Proposed Un-Balanced Non-Linear Load Condition.

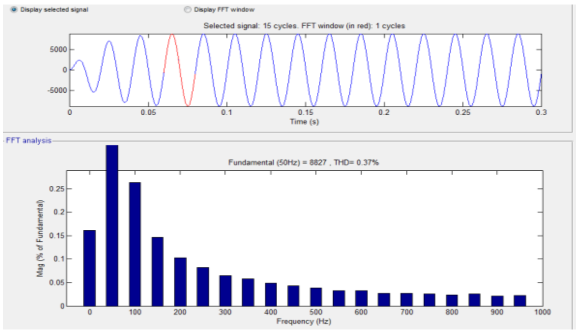


Fig.14 FFT Analysis of Source Current of Proposed unbalanced Non Linear Load Condition

CONCLUSION

The aim of this project was the analysis of a Modular Multilevel Converter (MMC) for different loading conditions and the development of a control scheme to monitor the energy behavior. To check the performance of loading conditions are linear & non-linear loads in both cases balanced and unbalanced conditions. The analysis was based on the use of a simplified circuit, constituted by a single leg of the converter, where all the modules in each arm were represented by a single variable voltage source. The circuit model was derived as a system of differential equations, used for analyzing both the steady state and dynamic behavior of the MMC, from voltages and thus energy point of view. The main aim of this concept D-STATCOM system based on the MMC circuit a novel control strategy with a focus on dc voltage control has been proposed according to the sufficient power-flow analysis. The D-STATCOM system, along with the proposed control strategy, is capable of compensating seriously unbalanced nonlinear load in an unbalanced power-supply system while keeping all of the dc-link voltages of capacitors. These all simulation results are verified by using Matlab/simulink software

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