An Optimal Combination Modulation Strategy for a Seven-level Cascade Multilevel Converter Based STATCOM

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Abstract — **This paper proposes an optimal modulation strategy for a Static Synchronous Compensation (STATCOM) using a seven-level cascade multilevel converter without any filter. Cascade multilevel converters have been used in STATCOM application due to its ability to reduce harmonics and increase output power by increasing the level of output voltages for a given semiconductor device without device series connection. Challenges in high power application include relatively low switching frequency (few hundred hertz to 1 kHz) limited by the thermal handling capability of semiconductor switch, and the low harmonic requirement specified by IEEE 519 Standard. With carrier based PWM, the STATCOM can generate lower current harmonic distortions at the expense of working at higher switching frequency. If step modulation strategy is used, the inverter works with lower switching frequency, but the STATCOM injects higher current harmonic distortions to power system, which generally leads to usage of extra filters. The proposed optimal combination modulation strategy works with low switching frequency and has low current harmonic distortions. The simulation results show that it can satisfy the device thermal requirements and IEEE 519 harmonic requirements simultaneously.**

Keywords-optimal moduation; cascade multilevel inverter; multilevel converter; STATCOM

I. INTRODUCTION

In recent years, increasing attention has been paid to multilevel dc/ac converters that have emerged as the solution for high power applications, since it is hard to use single power semiconductor switch directly in medium-voltage networks [1]. Cascade multilevel inverters that are based on the connection of several H-bridges are very popular among the existing topologies of multilevel inverters due to their modularization, extensibility and simpler control [2]. One of most important applications of cascade multilevel inverters is Static Synchronous Compensation (STATCOM) [3], which is a flexible AC transmission system (FACTS) device connected as a shunt to the network for generating or absorbing reactive power. STATCOM can be utilized to regulate voltage, control power factor and stabilize power flow.

A case of a three-phase seven-level cascade multilevel inverter without additional filter for a 10 MVAr STATCOM is investigated in the paper. The coupling voltage of the STATCOM is set as 4.16 kV and power flowing through transmission line is 64 MW. 4 kA/4.5 kV Emitter Turn-Off (ETO) thyristors [4] with heat pipe cooling system are used in the cascade multilevel inverter. Removal capability of the heat pipe is about 4 kW per device when double side cooling is used. Due to the high nominal current rating of 1.39 kA, from the thermal point of view, the switching frequency of the ETO is limited below about 500 Hz.

IEEE 519 standard [5] should be met if the STATCOM are connected in a power system. That is, current harmonic distortions caused by the STATCOM should be lower than the limits stated in IEEE 519 standard. With the step modulation [3, 6], the inverter works at lower frequency, but the current harmonic distortions are higher than the limits stated in the standard. The carrier based multilevel PWM [7, 8] can result in lower current harmonic distortions, but the switching frequency needs to be higher than 500 Hz. In [9, 10], the low order harmonics are eliminated by using resultant theory [11] while specified higher order harmonics are eliminated by Newton climbing method. This method can eliminate a great amount of specified order harmonics, but the higher switching frequency is still necessary. A new modulation strategy is proposed in the paper to satisfy the requirements of lower current distortions and lower switching frequency at the same time.

II. SYSTEM CONFIGURATION OF STATCOM

The STATCOM system is shown in Fig. 1. A step down transformer, 69 kV / 4.16 kV, is connected between the power system and the STATCOM. The designed nominal current rating is therefore 1.39 kA in order to achieve 10 MVAr. Each phase of the ETO-based seven-level cascade multilevel inverter used in the STATCOM consists of three H-bridges connected in series as shown in Fig. 2. Fig. 3 shows a modular H-bridge with heat pipes that can achieve higher power density, higher reliability and lower cost.

III. MODULATION STRATEGY

Modulation strategies used in the proposed STATCOM system should satisfy IEEE 519 interconnection requirements. Because the removal capability of the heat pipe is about 4 kW

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and a high nominal output current of 1.39 kA, the switching frequency of the ETO is limited to below 500 Hz. The step modulation has a merit of low switching frequency, but the current harmonic distortions exceed the limits of IEEE 519 standard. If the carrier based multilevel PWM strategy [7, 8] or the optimal PWM [9, 10] is applied, to achieve the requirement of current distortion limits, the switching frequency of ETO will be more than 500 Hz.

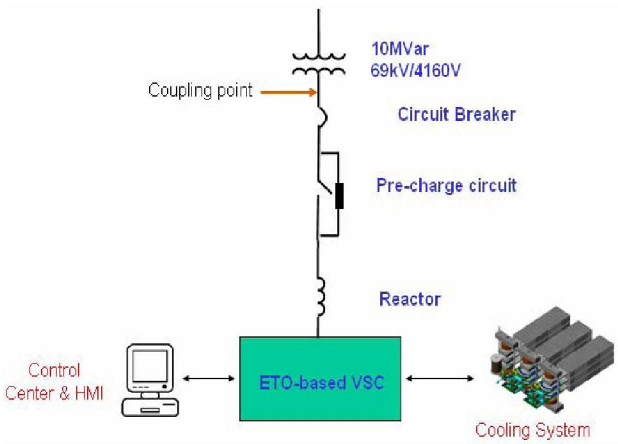

Fig. 1. Proposed ETO-based 10MVA STATCOM one line diagram.

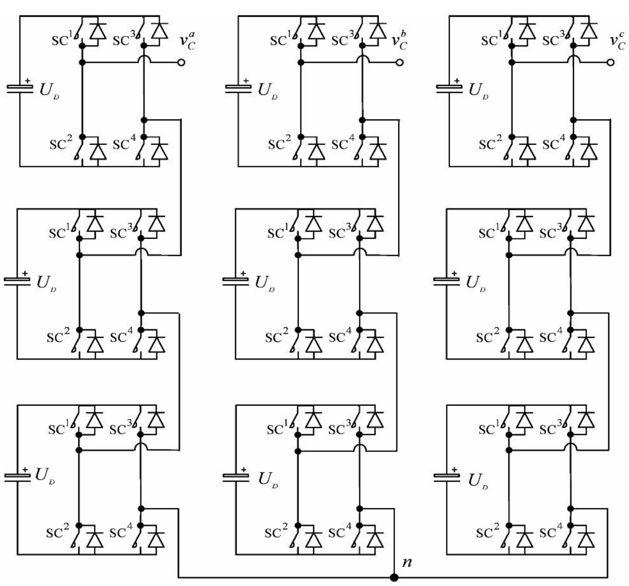

Fig. 2. Seven-level cascade multilevel inverter.

In this paper, a new optimal combination modulation strategy is proposed to stratify above requirements. Fig. 4 shows the optimal combination modulation strategy for the seven-level cascade multilevel inverter. v_{H1}, v_{H2} and v_{H3} are output voltages of three H-bridges each phase. As shown in Fig. 4, the output voltage of an H-bridge has five switching angles in the period from 0 to $\pi/2$. So the phase voltage of the inverter can achieve fifteen switching angles in the period from 0 to $\pi/2$. Based on Fourier series transformation, the harmonics of v_{H1} can be expressed as:

$$V_{H1(n)} = \frac{4U_D}{n\pi}[\cos(n\theta_1) - \cos(n\theta_2) + \cos(n\theta_3) - \cos(n\theta_4) + \cos(n\theta_5)] \quad (1)$$

where U_D is the voltage of dc capacitor of a H-bridge. Ideally, given a desired amplitude of fundamental component of v_{H1}, one wants to determine the switching angles to make specific harmonics be zero. For a three-phase application, the triple-order harmonics in each phase need not be canceled as they automatically cancel in the line-to-line voltages. Here, the 5th, 7th, 11th and 13th order harmonics are chosen to be removed. Suppose $V_{H1(1)}$ is the amplitude of fundamental component of output voltage of the first H-bridge. The switching angles of the first H-bridge must satisfy the following equations:

$$\begin{aligned}
&V_{H1(1)} = \frac{4U_D}{\pi}[\cos(\theta_{11}) - \cos(\theta_{12}) + \cos(\theta_{13}) - \cos(\theta_{14}) + \cos(\theta_{15})] \\
&0 = \cos(5\theta_{11}) - \cos(5\theta_{12}) + \cos(5\theta_{13}) - \cos(5\theta_{14}) + \cos(5\theta_{15}) \\
&0 = \cos(7\theta_{11}) - \cos(7\theta_{12}) + \cos(7\theta_{13}) - \cos(7\theta_{14}) + \cos(7\theta_{15}) \qquad (2) \\
&0 = \cos(11\theta_{11}) - \cos(11\theta_{12}) + \cos(11\theta_{13}) - \cos(11\theta_{14}) + \cos(11\theta_{15}) \\
&0 = \cos(13\theta_{11}) - \cos(13\theta_{12}) + \cos(13\theta_{13}) - \cos(13\theta_{14}) + \cos(13\theta_{15})
\end{aligned}$$

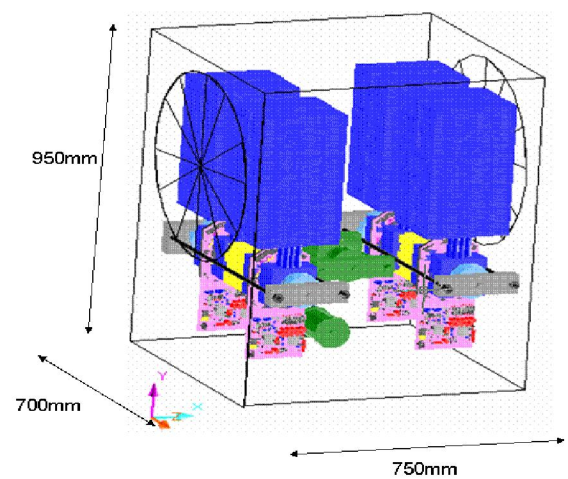

Fig. 3. Modular ETO-based H-bridge.

We can define the modulation index of the first H-bridge as:

$$M_{H1} = V_{H1(1)} / U_D \quad (3)$$

The resultant method is used here to find the solutions. The solutions exist in a range of the modulation indices from 0 to 1.16. Some modulation indices have no solutions, but some modulation indices have more than one solution.

In a phase, the seven-level cascade multilevel inverter can be viewed as three H-bridges connected in series, and these H-bridges can be controlled independently. The control method inherently cannot generate lower order harmonics (5th, 7th, 11th and 13th) since each H-bridge does not generate them. The modulation index for a phase is defined as:

$$M = V_{p(1)}/V_{dc} \tag{4}$$

where $V_{p(1)}$ is the amplitude of fundamental component of a phase voltage of the inverter and V_{dc} is the addition of dc link voltages of H-bridges each phase. The output voltages of three phases of the inverter are symmetric, so M is also the modulation index for the inverter. In the seven-level cascade multilevel inverter, the dc link voltages of H-bridges are identical, so

$$V_{dc} = 3U_D \tag{5}$$

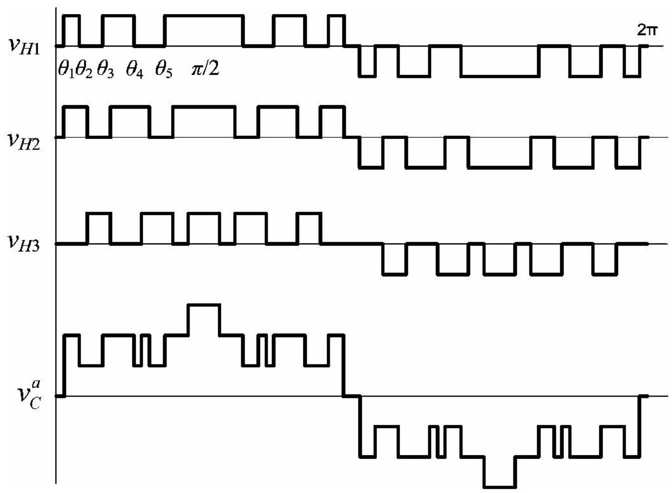

Fig. 4. Optimal PWM modulation strategy.

The modulation index is the addition of the modulation indices of H-bridges in a phase multiplied by polar index c_i.

$$M = \frac{1}{3}\sum_{i=1}^{3} c_i M_{Hi} \tag{6}$$

c_i can be 1, 0 or -1, which represents the output voltage of the ith H-bridge is positive, zero or negative with respect to the output voltage of the phase leg voltage.

The available value of the H-bridge modulation index, M_{Hi}, is from 0 to 1.16 and the resolution of M_{Hi} is set as 0.01. The algorithm to calculate the switching angles is shown as follows.

Step 1. We can get $116^3 \times 3^3 = 42144192$ combinations of $[M_{H1}, M_{H2}, M_{H3}, c_1, c_2, c_3]$ with respect to an M, and then pick up the combinations which satisfy (6).

Step 2. For each M_{Hi}, there are up to three sets of solutions of switching angles. For each resulting combination gotten from step 1, we can get up to $3^3 = 27$ combinations of $[\theta_{11}, \theta_{12}, \theta_{13}, \theta_{14}, \theta_{15}, c_1, \theta_{21}, \theta_{22}, \theta_{23}, \theta_{24}, \theta_{25}, c_2, \theta_{31}, \theta_{32}, \theta_{33}, \theta_{34}, \theta_{35}, c_3]$.

Step 3. For a combination, $[\theta_{11}, \theta_{12}, \theta_{13}, \theta_{14}, \theta_{15}, \theta_{21}, \theta_{22}, \theta_{23}, \theta_{24}, \theta_{25}, \theta_{31}, \theta_{32}, \theta_{33}, \theta_{34}, \theta_{35}, c_1, c_2, c_3]$, the harmonics of phase leg voltages can be expressed as

$$V_{(n)} = \sum_{i=1}^{3} \frac{4c_i U_D}{n\pi}[\cos(n\theta_{i1}) - \cos(n\theta_{i2}) + \cos(n\theta_{i3}) - \cos(n\theta_{i4}) + \cos(n\theta_{i5})] \tag{7}$$

The THD for the line-to-line voltage is defined as:

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} V_{(n)}^2}}{V_{(1)}} \quad (n = 5, 7, 11, 13, 17\ldots) \tag{8}$$

The current harmonics injected to the system are also calculated based on parameters of the STATCOM and the power system. IEEE 519 standard specifies the limits of voltage harmonics, THD, current harmonics and Total Demand Distortion (TDD). Only the combinations, $[\theta_{11}, \theta_{12}, \theta_{13}, \theta_{14}, \theta_{15}, c_1, \theta_{21}, \theta_{22}, \theta_{23}, \theta_{24}, \theta_{25}, c_2, \theta_{31}, \theta_{32}, \theta_{33}, \theta_{34}, \theta_{35}, c_3]$, meet all requirements stated in the IEEE 519 standard are chosen.

Step 4. For each combination, $[\theta_{11}, \theta_{12}, \theta_{13}, \theta_{14}, \theta_{15}, c_1, \theta_{21}, \theta_{22}, \theta_{23}, \theta_{24}, \theta_{25}, c_2, \theta_{31}, \theta_{32}, \theta_{33}, \theta_{34}, \theta_{35}, c_3]$, chosen from step 4, we can derive six different combinations, such as, $[A_1, A_2, A_3]$, $[A_1, A_3, A_2]$ and $[A_3, A_2, A_1]$, where A_i is $(\theta_{i1}, \theta_{i2}, \theta_{i3}, \theta_{i4}, \theta_{i5}, c_i)$.

Step 5. For each modulation index, find out all combinations that satisfy all conditions described from step 1 to step 4. From these combinations, we choose a combination, $[A_\alpha, A_\beta, A_\gamma]$, whose switching angles are the closet to the switching angles with respect to the adjacent modulation index. That is, the distance between the switching angles of adjacent modulation indices,

$$\sum_{i=1}^{5}(\theta_{\alpha i} - \eta_{1i})^2 + \sum_{i=1}^{5}(\theta_{\beta i} - \eta_{2i})^2 + \sum_{i=1}^{5}(\theta_{\gamma i} - \eta_{3i})^2$$

is the lest, where the switching angles with respect to the adjacent modulation index are $[\eta_{11}, \eta_{12}, \eta_{13}, \eta_{14}, \eta_{15}, \eta_{21}, \eta_{22}, \eta_{23}, \eta_{24}, \eta_{25}, \eta_{31}, \eta_{32}, \eta_{33}, \eta_{34}, \eta_{35}]$. This method can result in that the variations of the switching angles are much smoother.

IV. Case Study

The case studied in the paper is a 10 MVAr STATCOM system connected to a transmission line of 64 MW. The inductance of the coupling inductor is 0.6886 mH. IEEE 519 standard states that the percentage of 5th, 7th, 11th and 13th harmonics of transmission line current caused by the STATCOM must be less than 2%, the percentage of the 17th and 19th harmonics of that must be less than 1.5%, the percentage of 23rd, 25th, 29th and 31st harmonics of that must be less than 0.6%, the percentage of 35th and higher harmonics of that must be less than 0.3%, and TDD must be less than 5%.

Based on the propose optimal PWM modulation strategy and IEEE 519 requirement, the switching angles for the first H-bridge, the second H-bridge and the third H-bridge are calculated and shown in Fig. 5, Fig. 6 and Fig. 7 respectively.

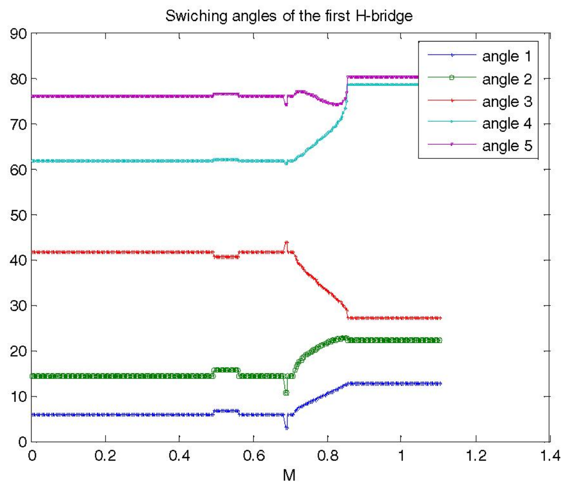

Fig. 5. Switching angles of the first H-bridge

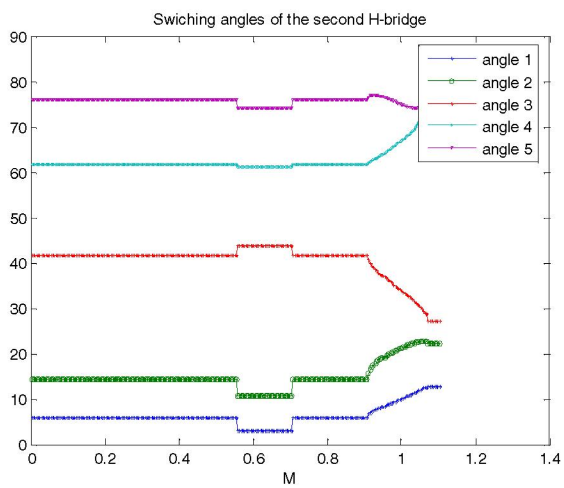

Fig. 6. Switching angles of the second H-bridge

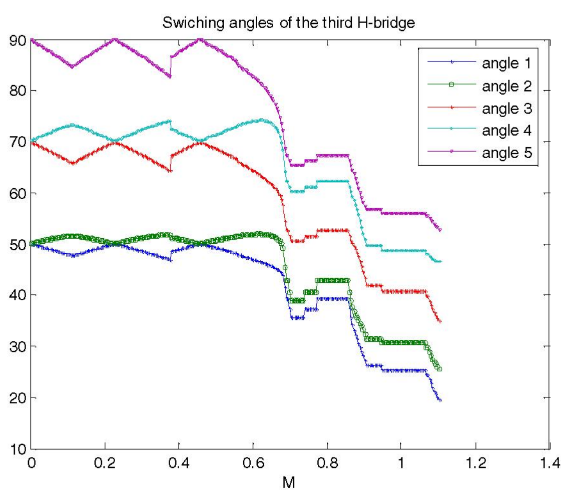

Fig. 7. Switching angles of the third H-bridge

V. Simulation Results

The performance of the modulation strategy presented above has been verified by simulation. The simulation investigations were performed with MATLAB Simulink.

Fig. 8 shows simulation waveforms of active power, reactive power, phase currents and voltages that the STATCOM outputs. As shown in Fig. 8, the STATCOM has rapid dynamic response.

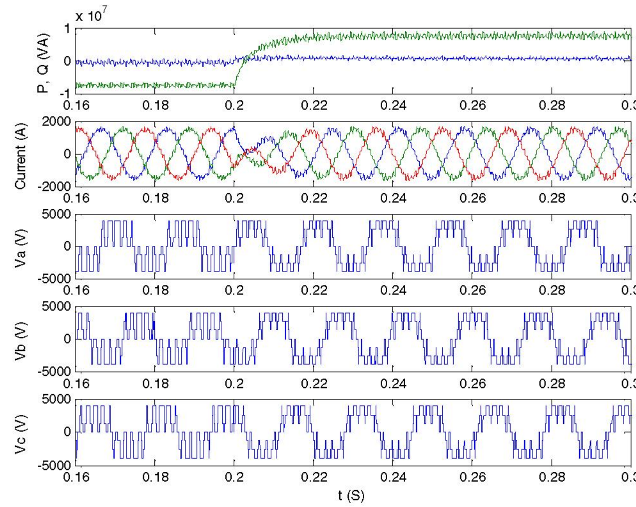

Fig. 8. Simulation waveforms for a step change of reference reactive power

Current harmonic components injected into the transmission line are also measured by simulation and shown in Fig. 9, Fig. 10, Fig. 11 and Fig. 12. The percentages of 5th, 7th, 11th and 13th harmonics of transmission line current caused by the STATCOM are less than 2%. The percentages of the 17th and 19th harmonics of transmission line current caused by the STATCOM are less than 1.5%. The percentages of 23rd, 25th, 29th and 31st harmonics of transmission line current caused by the STATCOM are less than 0.6%. The percentages of higher order harmonics of transmission line current caused by the STATCOM are less than 0.3%. TDD of transmission line current caused by the STATCOM is shown in Fig. 13. It is less than 5%. Therefore, the percentages of lower order harmonics and the TDD are less than the IEEE 519 current limits.

VI. Conclusion

A new optimal combination modulation strategy is proposed in the paper for the 10 MVAr STATCOM system. There are two optimizations in this strategy: the first one is the optimization of switching angles for each H-bridge to eliminate the 5th, 7th, 11th, and 13th harmonics, and the second one is the optimization of combination of switching angles of three H-bridges to minimize the higher order harmonics to meet IEEE 519 standard for a specified application. Compared with existing modulation strategies, the new modulation strategy can achieve lower THD and lower current harmonic distortion with lower switching frequency at the same time.

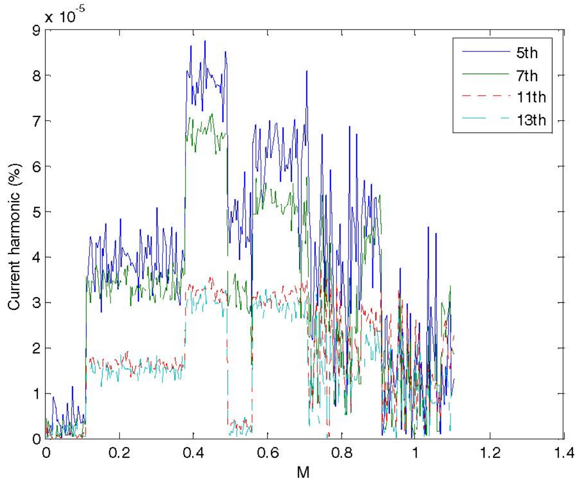

Fig. 9. Percentage of 5th 7th, 11th and 13th harmonics.

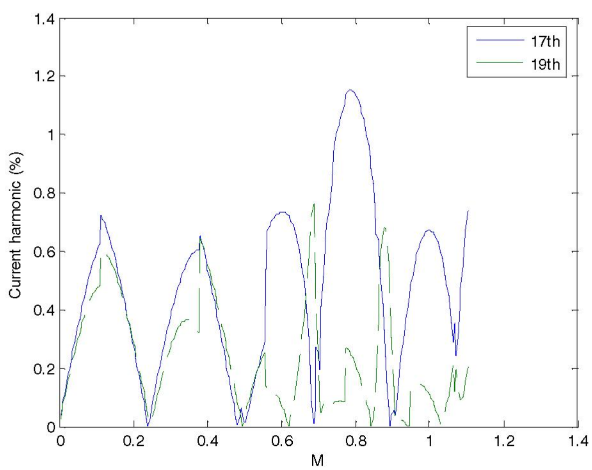

Fig. 10. Percentage of 17th and 19th harmonics.

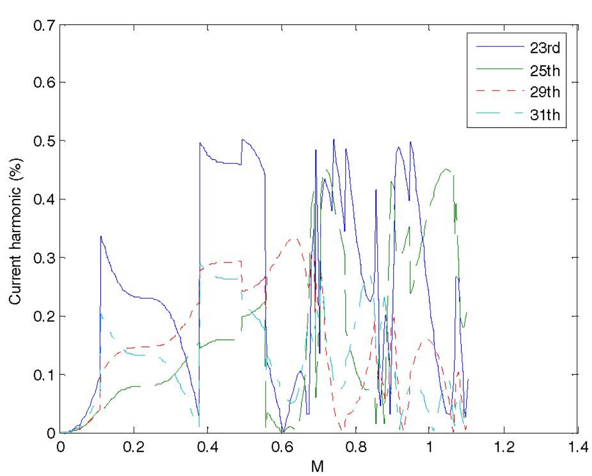

Fig. 11. Percentage of 23rd, 25th, 29th and 31st harmonics.

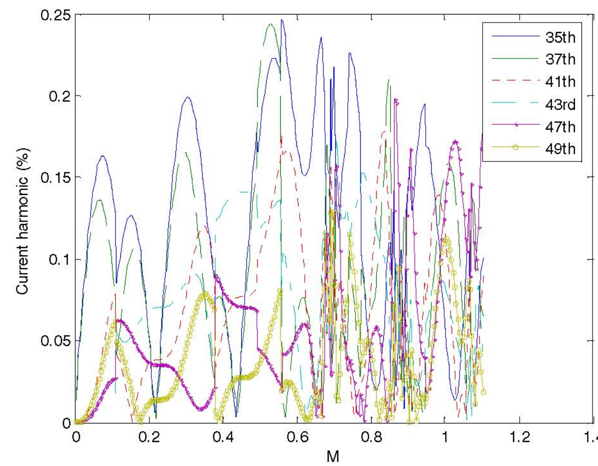

Fig. 12. Percentage of 35th and higher order harmonics.

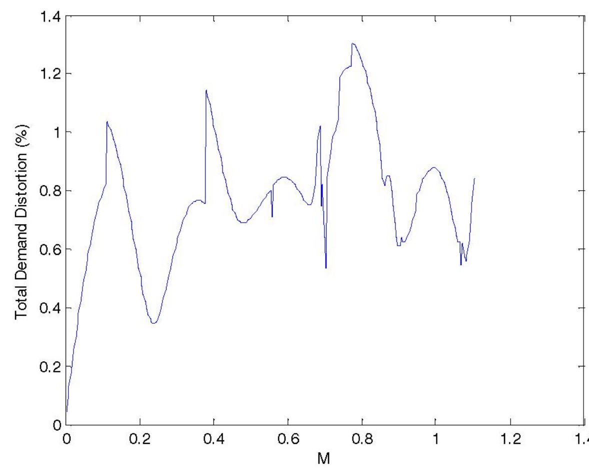

Fig. 13. TDD of transmission current caused by the STATCOM.

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