Analysis of Current Ripples to Design an LCL Filter for Grid-Connected Three-Level Inverters

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***Abstract*— LCL filters are widely used to achieve lower current harmonics in gird-connected converter systems. However, moat current research on LCL filters is aimed at two level inverters, while studies on multi-level inverters are not so common. In this paper, the maximum of ripple current is deduced through analysis of the current transient process, first. Then, based on LCL filter model for high order harmonics, the impact on ripple inhibition and resonant frequency caused by different filter parameters and scale factors is analyzed. While satisfying the filter effect, converter current harmonics are reduced as low as possible to determine inductance ratio and capacitance.** And **this provides a basis for the design of LCL output filter parameters. Finally, calculations are made and both the simulation and experiment results verify the validity and feasibility of the proposed design method.**

Keywords-three-level inverter, LCL filter, harmonic, ripple

I. INTRODUCTION

Along with the popularization and application of new energy sources such as photo-voltaic, wind energy and so on, the grid-connected inverter is getting more and more attention [1]. Compared to two-level grid-connected inverters at the same switching frequency, three level grid-connected inverters present lower harmonic distortion of the output voltages. Inverters using three-level topology can not only be used to output high capacity and high quality power with relatively small capacity switching device, but also the blocking voltage of the power switching devices is half of the dc-link voltage at the same time [2]. Due to its high stress levels, low du/dt and low harmonic content of output waveform, the three level inverter has become a new research hot spot [3]. In the selection of the output filter, because three-level grid-connected inverter is usually used in a large capacity, considering the size of the filter, the cost and other issues, LCL filter is usually selected. The LCL filters are widely used in ac drive systems since their improving harmonic performance at lower switching frequencies and reducing total inductance values. The first step of the design of LCL filters is the selection of the total inductance value. A lot of papers introduce the design of LCL filter based on two level inverter, however the study involving multi-level inverter is much less.

In this paper, with three-level voltage inverter as the study object, the ripple current of the inductor current in a switching period is analyzed. And the maximum of the current ripple is achieved, which contributes to the design of LCL filter. So L filter is designed at first, which means that the total inductance of LCL filter is achieved. The maximum of the inductance value is determined by the power condition, while the minimum is determined by the current ripple condition. After that, based on the traditional LCL filter parameter design and considering of stability, the influence the harmonic content and resonant frequency caused by scale factor and capacitance parameter is analyzed, and the design scheme of output LCL filter for three level inverter is proposed. Finally, the Matlab simulation model is established, and a set of experimental platform based on DSP-CPLD is built, which verifies the correctness of the proposed method, which has high value of application.

II. RIPPLE CURRENT ANALYSIS

Among all multi-level topologies, three-level neutral point clamped (NPC) inverter is the most widely used at present. The grid connected system comprises a NPC inverter and a low-pass output LCL filter as shown in Fig.1.

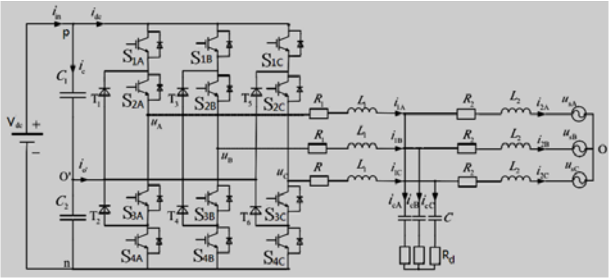


Fig. 1. System topology of grid-connected three level.

Each leg of the NPC inverter consists of four power switches (IGBT), four freewheeling diodes and two clamping diodes that limit the voltage excursions across each device to half the input dc-bus voltage. For three-level NPC inverter, each bridge leg has three different switching states. Define three phase switching states as:

$$S_j=\begin{cases}1 &, \ S_{1j}\text{ and }S_{2j}\text{ turn on}\\ 0 &, \ S_{2j}\text{ and }S_{3j}\text{ turn on} \qquad (j=A,B,C)\\ -1 &, \ S_{3j}\text{ and }S_{4j}\text{ turn on}\end{cases} \tag{1}$$

In order to simplify the mathematic model of grid-connected inverter, assume the LCL filter to be a single L filter, there is [4, 5]:

$$L\frac{d}{dt}\begin{bmatrix}i_A\\ i_B\\ i_C\end{bmatrix}=\begin{bmatrix}u_A\\ u_B\\ u_C\end{bmatrix}-\begin{bmatrix}u_{SA}\\ u_{SB}\\ u_{SC}\end{bmatrix}-\begin{bmatrix}u_{OO'}\\ u_{OO'}\\ u_{OO'}\end{bmatrix} \tag{2}$$

Where

$$\begin{bmatrix}u_A\\ u_B\\ u_C\end{bmatrix}=\begin{bmatrix}S_A\\ S_B\\ S_C\end{bmatrix}\cdot\frac{V_{dc}}{2} \tag{3}$$

$$u_{OO'}=\frac{1}{3}(S_A+S_B+S_C)\cdot\frac{V_{dc}}{2} \tag{4}$$

Where V_{dc} is the total DC bus voltage.

For the NPC three-level inverter, the voltage of filtering inductor of each phase is decided by switching states of three phases, there exists strong coupling relationship among three phases. If the coupling relationships among phases and all switching states are taken into consideration, the analysis becomes too complex to be made. Therefore, only the worst possible case is analyzed for simplification.

Under steady state condition, when the current reaches the peak value, the ripple current is most serious. So the current transient process in a switching period at the current peak is the key points of ripple analysis. In order to simplify the analysis, assume that inverter is controlled by unit power factor, when the current reaches the peak value, the power grid voltage reaches its peak value too, the rate of current and voltage is zero at the same time. Take the positive half cycle of phase A With L filter as an example.

Let T_{on} be the turn-on time of S_{1A} within a switching period T_S. The transient process is shown as in Figure.2.

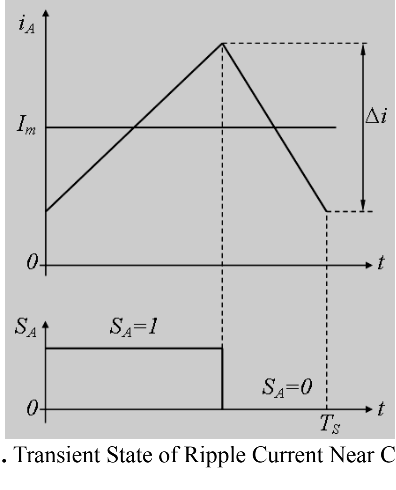


Fig. 2. Transient State of Ripple Current Near Current Peak.

Under steady state during $0\le t\le T_{on}$, $S_A=1$, According to formula (1) there is:

$$L_T\frac{\Delta i}{T_{on}}+E_m+\frac{V_{dc}}{3}(1+S_B+S_C)=\frac{V_{dc}}{2} \tag{5}$$

Where L_T is the inductance value of L filter, Δi is the current ripple; E_m is peak value of grid phase voltage.

When $T_{on}\le t\le T_S$, S_A=0, there is:

$$-L_T\frac{\Delta i}{T_S-T_{on}}+E_m+\frac{V_{dc}}{3}(S_B+S_C)=0 \tag{6}$$

Combine (5) and (6), and eliminating T_{on}, one equation can be obtained as follows:

$$\frac{L_T\Delta i}{T_S}=6V_{dc}\left(\frac{1}{6}-\left(\frac{E_m}{V_{dc}}+\frac{S_B+S_C}{3}\right)\right)\left(\frac{E_m}{V_{dc}}+\frac{S_B+S_C}{3}\right) \tag{7}$$

Define $\alpha=\frac{1}{6}-\left(\frac{E_m}{V_{dc}}+\frac{S_B+S_C}{3}\right)$, there is:

$$\frac{L_T\Delta i}{T_S}=-6V_{dc}\left(\alpha-\frac{1}{6}\right)^2+\frac{V_{dc}}{6} \tag{8}$$

As is known, $\frac{E_m}{V_{dc}}$ is approximately equal to 0.5, so when $S_B+S_C=-1$, the current ripple reaches to the maximum value:

$$\Delta i_{\max}=\frac{V_{dc}T_S}{6L_T} \tag{9}$$

III. DESIGN OF L FILTER

When the three-level grid-connected inverter operates with unity power factory under steady state conditions, the ability of active power output is considered, the inductance value of L filter should meet the challenge of the inverter output power [6]. The constraint on the inductance can be derived in (10):

$$L_T\le\frac{\sqrt{M^2{V_{dc}}^2-{E_m}^2}}{2\pi fI_m} \tag{10}$$

Where, M is the modulation coefficient; f is the fundamental frequency of the power grid.

Also, the inductance value of L filter should ideally restrain the current ripple, for too large ripple may influence loss of power electric switches and implication of control strategies. In practice, the maximum of the ripple current is ten percent of the peak value of the rated current [7]. In order to meet the requirements of the maximum ripple current, make $\Delta i_{\max}=0.1I_m$ and substitute into equation (9), there is:

$$L_T \geq \frac{5V_{dc}T_S}{3I_m} \tag{11}$$

According to (10) and (11), the range of total inductance can be determined. In order to improve the current tracking capacity and dynamic response of the system, L_T should be as small as possible, which usually takes the lower limit.

IV. DESIGN OF LCL FILTER

A. Mathematical Model of LCL Filter

Since the output of inverter does not contain low order harmonics, the power grid voltage is equivalent to a short circuit when higher harmonics are concerned only. Thus, the single phase equivalent circuit of the LCL filter can be obtained as shown in Figure 3.

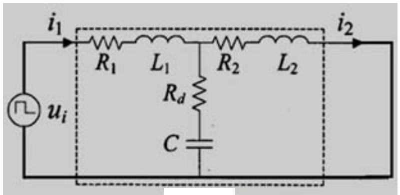


Fig.3. Single-Phase Equivalent Circuit of High Order Harmonic.

The equivalent resistance R_1 and R_2 are usually small, if the resistance is ignored, we can get the LCL filter's transfer function from voltage of the bridge side to the current of the grid side [8, 9]:

$$G(s)=\frac{I_2(s)}{U_1(s)}=\frac{R_dCs+1}{L_1L_2Cs^3+(L_1+L_2)R_dCs^2+(L_1+L_2)s} \tag{12}$$

When R_d is ignored, there is:

$$G(s)=\frac{1}{L_1L_2Cs^3+(L_1+L_2)s}=\frac{1}{1+(\frac{s}{w_{res}})^2}\cdot\frac{1}{(L_1+L_2)s} \tag{13}$$

Where w_{res} is the resonance angular frequency of LCL filter:

$$w_{res}=\sqrt{\frac{L_1+L_2}{L_1L_2C}} \tag{14}$$

Too high or too low resonant frequency of the LCL filter should be avoid. The resonant frequency of the LCL filter should be better 10 times greater than the grid frequency, and less than half of the switching frequency [10]:

$$10w_f \leq w_{res} \leq 0.5w_s \tag{15}$$

Where w_f is the fundamental frequency; w_s is the switching frequency.

Since harmonic wave centralizes around the switching frequency, the design in this paper mostly reviews the switching frequent harmonic attenuation. Substituting (16) into (14), there is:

$$\left|\frac{I_2(s)}{U_1(s)}\right|_{s=jw_s} \leq \frac{1}{3}\cdot\frac{1}{(L_1+L_2)w_s} \tag{16}$$

According to (17), it is clear that the total inductance value of LCL filter is one third of the single L filter to achieve the same filtering effect without taking resonance into account. While taking resonance of LCL filter into account, the total inductance value should be larger to a certain extent. Take the magnification factor to be 1.5, there is:

$$L_1+L_2=1.5\times\frac{L_T}{3}=0.5L_T \tag{17}$$

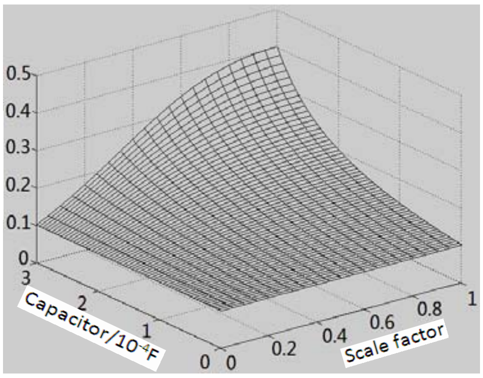
B. Impact of Scale Factor and Capacitance

Define the scale factor as $\lambda=L_2/L_1$.In consideration of the ripple current of the inverter bridge is decided by L_1 mainly, and higher ripple current will lead to larger loss of switching and loss on the inductor. Therefore, the inductance of the bridge side is usually greater than the power grid side, so the value of scale factor is lower than 1.

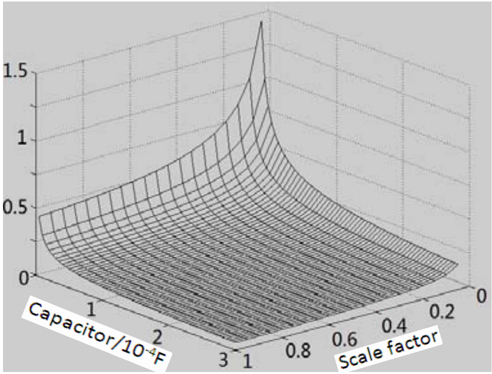
Except for the attenuation requirement of the grid-side harmonic current, LCL filter should absorb the fundamental reactive power as little as possible, make the ripple of the bridge-side current as small as possible, and meanwhile ensure the requirement of the resonant frequency. Therefore, the influences of changing of the scale factor and the capacitance on the filtering effect and the resonant frequency are mainly considered flowingly.

According to the formula (14) and (15), impact on filtering effect and resonant frequency caused by the scale factor and capacitance are shown as in Fig. 4 respectively.

The filtering effect of certain harmonic affected by different scale factor and capacitance is shown in Figure 4(a). It is clear that with increasing of the capacitance, amplitude of harmonic becomes higher. While total inductance is settled, the resonant frequency affected by different scale factor and capacitance is shown in Figure 4(b). It can be seen that for the same capacitance, higher scale factor lead to higher current harmonic amplitude.



(a) relationship between |G(jw)| and λ,C



(b) relationship between resonant frequency and λ,C

Fig.4. Impact on Filter Effect and Resonant Frequency Caused By λ and C.

Also, the resonant frequency becomes lower if capacitance and scale factor are increased, which means better filtering effect of high order harmonic. The resonant frequency is very gentle while filter capacitance is between 30~300uF and scale factor is between 0.2~1. Take it into consider that increasing of capacitance and scale factor lead to increasing of harmonic content. Therefore the capacitance and scale factor had better to be selected near to the lower bound as far as possible. Take scale factor to be 0.2, and then, the inductance of the bridge-side and that of the grid-side can be concluded easily.

As for the filter capacitor, it is mainly used to meet the requirement of high frequency current decay rate. However, greater the capacitance is, more reactive power is produced, which leads to larger fundamental reactive current and lower power factor. It means that the current capacity of inverter is limited equivalently. In addition, the size of AC capacitor with large capacitance is big and expensive. Generally, the reactive power produced by the capacitor of LCL filter must not exceed 5% of the rating active power [11]:

$$C \le \frac{5\% P_n}{6\pi f E_n^{\ 2}} \tag{18}$$

Where P_n for rating active power; E_n for the rating phase voltage of the grid side.

Another purpose of introduction of the capacitor branch is to provide a low resistance path for high frequency components. The grid-side inductance and the filtering capacitor constitute a parallel circuit on the switching ripple content. In order to ensure shunt effect, the capacitor impedance must be much less than the inductor impedance of grid side. The proportion relationship exists between the impedance of capacitor and inductor is generally taken as 20% [8]. So the lower bound of the filter capacitance can be determined.

$$C \ge \frac{5}{4\pi^2 f_s^{\ 2} L_2} \tag{19}$$

Where f_s is switching frequency.

After the initial LCL parameters are determined, it is necessary to check the resonant frequency according to formula (15).

C. Design of Damping Resistance

After checking of the resonant frequency, design of the damping resistance can be carried out finally. According to bode diagram analysis of the transfer function based on formula (12), an conclusion can be made, that is, increasing damping resistor can enhance the damping coefficient and system stability. With the increasing of the damping resistor, the resonant peak value decreases. While damping resistance is 0.3~0.4 times of capacitor impedance, effect of the resonance peak suppression is satisfying. If we keep on increasing damping resistance, more damping loss would be afforded. So the calculation of the damping resistance can be determined by the following formula:

$$R_d = (0.3 \sim 0.4) X_C = (0.3 \sim 0.4) \frac{1}{w_{res} C} \tag{20}$$

V. CALCULATION, SIMULATION AND EXPERIMENT

A. Calculation

In order to demonstrate the design method of LCL filter proposed in this paper, taking a 50kW three-level inverter as example, which is connected with grid through transformer. Parameters are as follows:

TABLE 1. PARAMETERS CATEGORIES

Parameters	**Value**
Grid line voltage(RMS)	380 V
Load rate	50 KW
Transformer voltage ratio	380V / 315V
DC bus, V_d	600 V
Utility frequency, *f*	50 Hz
Sampling frequency	12.5 kHz
Switching frequency, f_s	12.5 kHz
Current peak, I_m	130 A

The calculation procedures are as follows:

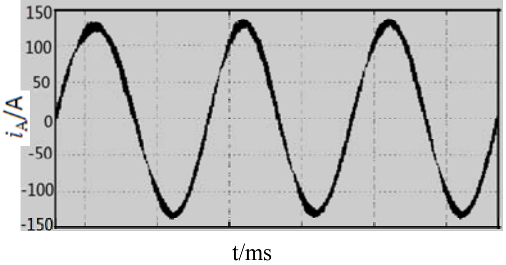
(1) For single L filter, according to formula (10), the inductance must not exceed 5.7 mH. According to formula (11), the inductance must be greater than 0.62mH, take it as 0.62mH. As for LCL filter, according to formula (17), the total inductance should be 0.31mH.

(2) Choose the scale factor to be 0.2, therefore inductance of the bridge side is 0.26mH, and inductance of the grid side is 0.05mH. According to formula (14), the capacitance should be less than 80.97uF, and must be greater than 10.81uF on the basis of formula (19). So the initial selection of capacitance could be 40uF.

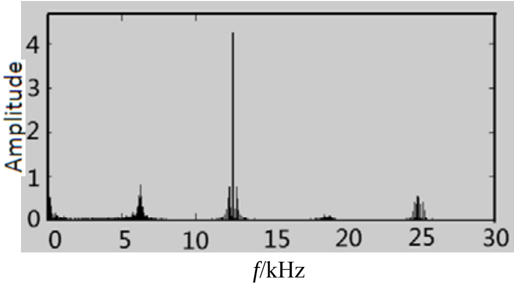
(3) When initial LCL parameters are settled, it can be calculated according to formula (14) that the resonant frequency of the LCL filter is 3825 Hz, which satisfies the requirement of the checking condition constrained by formula (15). Finally, the damping resistance can be calculated to be 0.32Ω according to formula (20).

B. Simulation

In order to verify the correctness of the filter parameters design, a simulation model based on Matlab/Simulink is established. Total harmonic distortion (THD) is shown in Figure 5. In Figure 5 (a), it can be found that the current ripple is most serious when the current reach to its peak value. After a fast Fourier transform, the spectrum is investigated, as shown in Figure 5 (b). It can be seen that harmonics are mainly concentrated at the switching frequency, and THD is 4.81%.

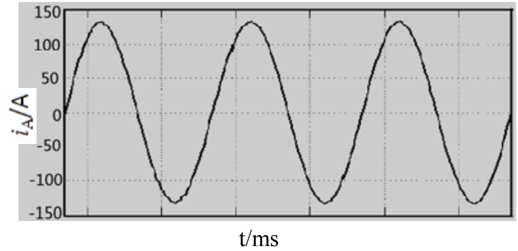


(a) A-phase arm side current waveform

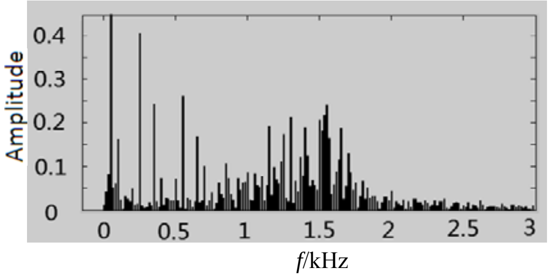


(b) FFT analysis of current waveform

Fig.5. Arm Side Current Waveform and Its FFT Analysis of A-phase.



(a) A-phase grid side current waveform



(b) FFT analysis of current waveform

Fig.6. Grid Side Current Waveform and Its FFT Analysis of A-phase.

Simulation results of the grid side current after LCL filtering are shown in figure 6. The THD of the grid side current is 0.71%, which has good filtering effect. It can be seen From figure 6 (b) that the harmonic contents are mainly located in frequency below 2.5kHz, which shows that the LCL filter can filter out high order harmonics successfully.

C. Experiment

In order to go a step further to verify the correctness of the design method, a set of experimental platform based on DSP-CPLD as the control core is set up, as shown in Fig 7.

Fig.7. Experimental Devices.

Phase current waveform under steady state of the bridge side and that of the grid side are shown in Figure 8. And with a power quality analyzer, it can be measured that THD of the grid side phase current is 1.87%, which means that the three level inverter system meet the requirements of the power grid.

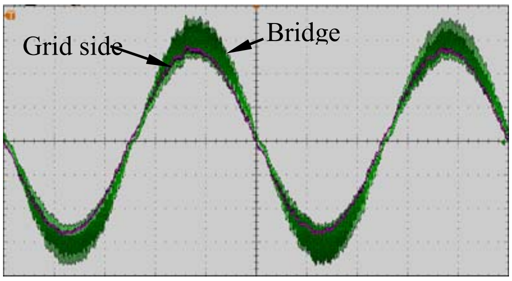


Fig.8. Steady-state Waveform.

VI. CONCLUSIONS

In this paper, the maximum of the ripple current is achieved on the basis of the analysis of the transient process of three-level grid-connected inverters. The range of the inductance of L filter is settled, which can be used to determine the total inductance of LCL filter. Also, the impact on filtering effect and resonant frequency caused by different capacitance and scale factor is analyzed based on LCL filter mathematic model for high order harmonic. And this provides a basis for design of LCL output filter parameters.

Finally, calculations are made to demonstrate the design method. Both the simulation and experiment research are also realized. The THD of the grid-tied current is rather small and the quality of the waveform is quite good, which verify the validity of the proposed method.

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APPENDIX

Detailed derivation process of fomula (8)

$$\because \begin{cases} L_T \dfrac{\Delta i}{T_{on}} + E_m + \dfrac{V_{dc}}{3}(1 + S_B + S_C) = \dfrac{V_{dc}}{2} \\ -L_T \dfrac{\Delta i}{T_S - T_{on}} + E_m + \dfrac{V_{dc}}{3}(S_B + S_C) = 0 \end{cases}$$

$$\therefore \begin{cases} L_T \dfrac{\Delta i}{T_{on}} + E_m + \dfrac{V_{dc}}{3}(S_B + S_C) = \dfrac{V_{dc}}{6} \\ -L_T \dfrac{\Delta i}{T_S - T_{on}} + E_m + \dfrac{V_{dc}}{3}(S_B + S_C) = 0 \end{cases}$$

$$\therefore \begin{cases} L_T \Delta i = T_{on}\left(\dfrac{V_{dc}}{6} - \left(E_m + \dfrac{V_{dc}}{3}(S_B + S_C)\right)\right) \quad * \\ L_T \Delta i = (T_S - T_{on})\left(E_m + \dfrac{V_{dc}}{3}(S_B + S_C)\right) \quad ** \end{cases}$$

According to * : $T_{on} = \dfrac{L_T \Delta i}{\dfrac{V_{dc}}{6} - \left(E_m + \dfrac{V_{dc}}{3}(S_B + S_C)\right)}$ ***

Substitute *** into ** :

$$\frac{L_T \Delta i}{E_m + \dfrac{V_{dc}}{3}(S_B + S_C)} = T_S - \frac{L_T \Delta i}{\dfrac{V_{dc}}{6} - \left(E_m + \dfrac{V_{dc}}{3}(S_B + S_C)\right)}$$

$$\therefore \quad L_T \Delta i \frac{V_{dc}}{6} = T_S\left(\frac{V_{dc}}{6} - \left(E_m + \frac{V_{dc}}{3}(S_B + S_C)\right)\right)\left(E_m + \frac{V_{dc}}{3}(S_B + S_C)\right)$$

$$\therefore \quad \frac{L_T \Delta i}{T_S} = 6V_{dc}\left(\frac{1}{6} - \left(\frac{E_m}{V_{dc}} + \frac{S_B + S_C}{3}\right)\right)\left(\frac{E_m}{V_{dc}} + \frac{S_B + S_C}{3}\right)$$

Define $\alpha = \dfrac{1}{6} - \left(\dfrac{E_m}{V_{dc}} + \dfrac{S_B + S_C}{3}\right)$

$$\frac{L_T \Delta i}{T_S} = 6V_{dc}\alpha(\frac{1}{6} - \alpha)$$

$$\therefore \quad \frac{L_T \Delta i}{T_S} = \alpha V_{dc} - 6V_{dc}\alpha^2 - \frac{V_{dc}}{6} + \frac{V_{dc}}{6}$$

$$\therefore \quad \frac{L_T \Delta i}{T_S} = -6V_{dc}(\alpha - \frac{1}{6})^2 + \frac{V_{dc}}{6}$$