International Journal of Science and Engineering Applications
Volume 13-Issue 06, 17 – 22, 2024, ISSN:- 2319 - 7560
DOI: 10.7753/IJSEA1306.1004

Capacitance and Inductance Selection in High Power Inverters

M. Jovanović
University of Belgrade
Serbia

Y. Jang
Yonsei University
Korea

Wu Chen
Power & Control Department
South China University of Technology
China

Abstract: The paper outlines a procedure for selecting capacitance and inductance for the modular multilevel converter. In the direct modulation method of the modular multilevel converter, sinusoidal modulating signals cause circulating currents to flow through the converter arms. These currents depend heavily on the component parameters of the converter, including the capacitance of the submodule DC-link capacitors and the inductance of the converter arms. Both components together form a series resonance circuit in each converter arm. It's crucial to avoid resonance in the converter arm, so it's important to carefully select component parameters while considering all potential resonances. This component selection process should be carried out early in the converter design stage.

Keywords: Capacitor, Circulating current, inductor, High Power Inverters, pulse wide modulation (PWM).

1. INTRODUCTION

MMC topologies are one of the most promising topologies for low- and medium-voltage applications because of their superior modularity, high reliability, flexibility, and superior harmonic performance [1]. The modular multilevel converter is the most promising topology in medium-voltage applications, such as motor drives [2] and power electronic transformers [3]. A number of articles also reported its application in photovoltaic systems [4], distributed energy storage [5], microgrids [6] and power flow controllers [7]. Neutral Point Clamped (NPC) converters are the most popular type of modular multilevel converters. The modeling of the three-level NPC voltage source inverter is represented mathematically under various fault conditions in [6]. In [8], different grounding architectures impacts on fault tolerability of NPC converters are evaluated in various fault conditions of AC and DC sides of the system. In [9], in order to eliminate dc ground currents in steady state, improve the sensitivity of ground fault protection in fault transients, limit the ground fault current, and consequently protect power electronic interfaces, a new grounding method for NPC converters is proposed.

The full-bridge converter is widely used in medium-to-high power dc–dc conversions because it can achieve soft-switching without adding any auxiliary switches [10]. IC used in [11] is a back-to-back connection of a full-bridge ac/dc converter with a half-bridge dc/dc converter through their common dc-link capacitor for unipolar hybrid microgrids. A back-to-back connection of two well-known topologies, a half-bridge dc/dc converter and a full-bridge ac/dc converter is used in [12] as an interface between AC and DC microgrids.

In Section 2, the capacitance selection process for a full bridge modular multilevel converter is explained, and in Section 3, the inductance selection process is explained. At the end, the outcomes are summarized in Section 4.

2. CAPACITANCE SELECTION

For the capacitance and inductance selection, it is assumed:

i_{ac} : ac-side current and i_{dc} : dc current.

$$v_{ac} = v_m \sin \omega t \quad (1)$$

$$i_{ac} = i_m \sin(\omega t + \varphi) \quad (2)$$

And with considering modulation index(m)

$$m = \frac{v_m}{V_{dc}/2} = 2\frac{v_m}{V_{dc}} \qquad 0 \le m \le 1 \qquad (3)$$

Modulation index gives the ratio that switches are on or off. In addition, current coefficient k

$$k = \frac{i_m/2}{i_{dc}/2} = \frac{i_m}{i_{dc}} \quad (4)$$

with neglecting inductor and resistor in arms, Voltage of upper and lower arms are:

A. Arm's Voltage

$$v_{u,j} = \frac{V_{dc}}{2} - v_{ac} = \frac{V_{dc}}{2} - v_m \sin \omega t = \frac{V_{dc}}{2} - \frac{m.V_{dc}}{2}\sin \omega t = \frac{V_{dc}}{2}(1 - m\sin \omega t) \qquad (5)$$

$$v_{l,j} = \frac{V_{dc}}{2} + v_{ac} = \frac{V_{dc}}{2} + v_m \sin \omega t = \frac{V_{dc}}{2} + \frac{m.V_{dc}}{2}\sin \omega t = \frac{V_{dc}}{2}(1 + m\sin \omega t) \qquad (6)$$

Arm's Current, according to (2) is as follows:

$$i_{u,j} = \frac{i_{dc}}{2} + \frac{i_{ac}}{2} = \frac{i_{dc}}{2} + \frac{i_m \sin(\omega t + \varphi)}{2} = \frac{i_{dc}}{2} + \frac{(k.i_{dc})\sin(\omega t + \varphi)}{2} = \frac{i_{dc}}{2}[1 + k\sin(\omega t + \varphi)] \qquad (7)$$

$$i_{l,j}=\frac{i_{dc}}{2}-\frac{i_{ac,j}}{2}=\frac{i_{dc}}{2}-\frac{i_m\sin(\omega t+\varphi)}{2}=$$
$$\frac{i_{dc}}{2}-\frac{(\mathrm{k}.i_{dc})\sin(\omega t+\varphi)}{2}=\frac{i_{dc}}{2}[1-k\sin(\omega t+\varphi)] \quad (1)$$

3. Arm's Power

In conclusion we have:

$$\begin{cases} v_{u,j}=\dfrac{V_{dc}}{2}(1-m\sin\omega t)\\ v_{l,j}=\dfrac{V_{dc}}{2}(1+m\sin\omega t)\end{cases} \quad (2)$$

And

$$\begin{cases} i_{u,j}=\dfrac{i_{dc}}{2}[1+k\sin(\omega t+\varphi)]\\ i_{l,j}=\dfrac{i_{dc}}{2}[1-k\sin(\omega t+\varphi)]\end{cases} \quad (3)$$

Then

$$P_{u,j}=v_{u,j}\times i_{u,j}=\frac{V_{dc}}{2}(1-m\sin\omega t)\times\frac{i_{dc}}{2}[1+k\sin(\omega t+\varphi)]$$
$$=\frac{V_{dc}\times i_{dc}}{4}(1-m\sin\omega t)[1+k\sin(\omega t+\varphi)] \quad (4)$$
$$=\frac{P_{dc}}{4}[k.\sin(\omega t+\varphi)-m\sin\omega t+\frac{\mathrm{m}k}{2}\cos(2\omega t+\varphi)]$$
$$+\frac{P_{dc}}{4}[1-\frac{\mathrm{m}k\cos(\varphi)}{2}]$$

That last expression equal to zero since in steady state transferred power in DC side is equal to AC side.

$$\frac{P_{dc}}{4}[1-\frac{\mathrm{m}k\cos(\varphi)}{2}]=0$$
$$\rightarrow 1=\frac{\mathrm{m}k\cos(\varphi)}{2}\rightarrow \mathrm{m}k=\frac{2}{\cos(\varphi)} \quad (5)$$

And

$$P_{l,j}=v_{l,j}\times i_{l,j}=\frac{V_{dc}}{2}(1+m\sin\omega t)\times\frac{i_{dc}}{2}[1-k\sin(\omega t+\varphi)]$$
$$=\frac{V_{dc}\times i_{dc}}{4}(1+m\sin\omega t)[1-k\sin(\omega t+\varphi)] \quad (6)$$
$$=\frac{P_{dc}}{4}[-k.\sin(\omega t+\varphi)+m\sin\omega t+\frac{\mathrm{m}k}{2}\cos(2\omega t+\varphi)]$$

Then in summary:

$$\begin{cases} P_{u,j}=\dfrac{P_{dc}}{4}[k.\sin(\omega t+\varphi)-m\sin\omega t+\dfrac{\mathrm{m}k}{2}\cos(2\omega t+\varphi)]\\ P_{l,j}=\dfrac{P_{dc}}{4}[-k.\sin(\omega t+\varphi)+m\sin\omega t+\dfrac{\mathrm{m}k}{2}\cos(2\omega t+\varphi)]\end{cases} \quad (7)$$

or

$$\begin{cases} P_{u,j}=\dfrac{P_{dc}}{6}(1-m\sin\omega t)[1+k\sin(\omega t+\varphi)]\\ P_{l,j}=\dfrac{P_{dc}}{6}(1+m\sin\omega t)[1-k\sin(\omega t+\varphi)]\end{cases} \quad (8)$$

From [13] to calculate energy swing in a branch ,first zeros of power of upper and lower arms should be determined:

$$P_{u,j}=0$$
$$\rightarrow(1-m\sin\omega t)[1+k\sin(\omega t+\varphi)]=0$$
$$\rightarrow\begin{cases}(1-m\sin\omega t)=0\\ [1+k\sin(\omega t+\varphi)]=0\end{cases} \quad (9)$$

To calculate zeros of voltage:

$$(1-m\sin\omega t)=0 \qquad \rightarrow\sin\omega t=\frac{1}{m} \quad (10)$$

And because

$$-1\le\sin\omega t\le 1 \quad (11)$$

Then

$$-1\le\frac{1}{m}\le 1 \quad (12)$$

But modulation index is between 0 and one ($0\le m\le 1$), so (17) cannot become zero. Then arms voltage does not produce zeros in swing power.

Now how about the other component:

$$[1+k\sin(\omega t+\varphi)]=0 \quad \rightarrow\sin(\omega t+\varphi)=-\frac{1}{k}$$
$$\rightarrow\omega t+\varphi=Arc\sin(-\frac{1}{k}) \rightarrow\begin{cases}\omega t=-\varphi-Arc\sin(\dfrac{1}{k})\\ \omega t=-\varphi+Arc\sin(\dfrac{1}{k})+\pi\end{cases} \quad (13)$$

Also power lower arm power:

$$P_{l,j}=0\rightarrow\begin{cases}\omega t=\pi+-\varphi-Arc\sin(\dfrac{1}{k})\\ \omega t=-\varphi+Arc\sin(\dfrac{1}{k})\end{cases} \quad (14)$$

Then for upper and lower arms' power:

$$\begin{cases} P_{u,j}=\dfrac{P_{dc}}{4}[k.\sin(\omega t+\varphi)-m\sin\omega t+\dfrac{\mathrm{m}k}{2}\cos(2\omega t+\varphi)]\\ P_{l,j}=\dfrac{P_{dc}}{4}[-k.\sin(\omega t+\varphi)+m\sin\omega t+\dfrac{\mathrm{m}k}{2}\cos(2\omega t+\varphi)]\end{cases} \quad (15)$$

$$\begin{cases} E_{u,j}=\int P_{u,j}\\ E_{l,j}=\int P_{l,j}\end{cases} \quad (16)$$

Then in conclusion:

$$\begin{cases} E_{u,j}=\dfrac{P_{dc}}{4\omega}[-k.\cos(\omega t+\varphi)+k\cos\omega t+\dfrac{\mathrm{m}k}{2}\dfrac{1}{2}\sin(2\omega t+\varphi)]\Big|_{t1}^{t2}\\ E_{l,j}=\dfrac{P_{dc}}{4\omega}[+k.\cos(\omega t+\varphi)-k\cos\omega t+\dfrac{\mathrm{m}k}{2}\dfrac{1}{2}\sin(2\omega t+\varphi)]\Big|_{t1}^{t2}\end{cases} \quad (17)$$

And from (12):

$$\begin{cases} E_{u,j}=\dfrac{P_{dc}}{4\omega}[\dfrac{\sin(2\omega t+\varphi)}{2.\cos\varphi}+2\dfrac{\cos\omega t}{k.\cos\varphi}-k.\cos(\omega t+\varphi)]\Big|_{t1}^{t2}\\ E_{l,j}=\dfrac{P_{dc}}{4\omega}[\dfrac{\sin(2\omega t+\varphi)}{2.\cos\varphi}-2\dfrac{\cos\omega t}{k.\cos\varphi}+k.\cos(\omega t+\varphi)]\Big|_{t1}^{t2}\end{cases} \quad (18)$$

That also presented in [3]. And from (20):

$$\begin{cases} t_1 = \dfrac{1}{\omega}\left(-\varphi - Arc\sin(\dfrac{1}{k})\right) \\ t_2 = \dfrac{1}{\omega}\left(-\varphi + Arc\sin(\dfrac{1}{k}) + \pi\right) \end{cases} \quad (19)$$

Then:

$$E_{u,j} = \frac{P_{dc}}{4\omega}\left[\frac{\sin(2\omega t+\varphi)}{2.\cos\varphi} + 2\frac{\cos\omega t}{k.\cos\varphi} - k.\cos(\omega t+\varphi)\right]\Bigg|_{t1}^{t2}$$

$$= \frac{P_{dc}}{4\omega}\left[\begin{array}{l}\left(\dfrac{\sin(-\varphi+2Arc\sin(\frac{1}{k})+2\pi)}{2.\cos\varphi} + 2\dfrac{\cos(-\varphi+Arc\sin(\frac{1}{k})+\pi)}{k.\cos\varphi} - k.\cos(Arc\sin(\frac{1}{k})+\pi)\right) - \\ \left(\dfrac{\sin(-\varphi-2Arc\sin(\frac{1}{k}))}{2.\cos\varphi} + 2\dfrac{\cos(-\varphi-Arc\sin(\frac{1}{k}))}{k.\cos\varphi} - k.\cos(-Arc\sin(\frac{1}{k})\right)\end{array}\right] \quad (20)$$

$$E_{u,j} = \frac{P_{dc}}{4\omega}\left[\begin{array}{l}\left(\dfrac{\sin(-\varphi+2Arc\sin(\frac{1}{k})+2\pi)}{2.\cos\varphi} - \dfrac{\sin(-\varphi-2Arc\sin(\frac{1}{k}))}{2.\cos\varphi}\right) + \\ \left(2\dfrac{\cos(-\varphi+Arc\sin(\frac{1}{k})+\pi)}{k.\cos\varphi} - 2\dfrac{\cos(-\varphi-Arc\sin(\frac{1}{k}))}{k.\cos\varphi}\right) + \\ \left(-k.\cos(Arc\sin(\frac{1}{k})+\pi) + k.\cos(-Arc\sin(\frac{1}{k}))\right)\end{array}\right] \quad (21)$$

For each expression:

$$\left(\frac{\sin(-\varphi+2Arc\sin(\frac{1}{k})+2\pi)}{2.\cos\varphi} - \frac{\sin(-\varphi-2Arc\sin(\frac{1}{k}))}{2.\cos\varphi}\right) = \frac{2}{k}\sqrt{1-\frac{1}{k^2}} \quad (22)$$

And:

$$\left(2\frac{\cos(-\varphi+Arc\sin(\frac{1}{k})+\pi)}{k.\cos\varphi} - 2\frac{\cos(-\varphi-Arc\sin(\frac{1}{k}))}{k.\cos\varphi}\right)$$

$$= \frac{2}{k.\cos\varphi}\left(\cos(-\varphi+Arc\sin(\frac{1}{k})+\pi) - \cos(-\varphi-Arc\sin(\frac{1}{k}))\right) = \quad (23)$$

$$= \frac{2}{k.\cos\varphi}\left(-2\sqrt{1-\frac{1}{k^2}}\cos\varphi\right) = \frac{-4}{k}\sqrt{1-\frac{1}{k^2}}$$

And:

$$\left(-k.\cos(Arc\sin(\frac{1}{k})+\pi) + k.\cos(-Arc\sin(\frac{1}{k}))\right) = 2\sqrt{1-\frac{1}{k^2}}k \quad (24)$$

Then:

$$E_{u,j} = \frac{P_{dc}}{4\omega}\left[\frac{2}{k} - \frac{4}{k} + 2k\right]\sqrt{1-\frac{1}{k^2}} \quad (25)$$

$$E_{u,j} = \frac{P_{dc}}{4\omega}\left[2k - \frac{2}{k}\right]\sqrt{1-\frac{1}{k^2}} = \frac{P_{dc}}{4\omega}2k\left[1-\frac{1}{k^2}\right]\sqrt{1-\frac{1}{k^2}} = \frac{P_{dc}}{2\omega}k\left[1-\frac{1}{k^2}\right]^{\frac{3}{2}} \quad (26)$$

For energy of each capacitor:

$$E = \frac{1}{2}C_{cell}V_{cell}^2 \quad (27)$$

Then with considering N cell in each arm of MMC, According to articles [13] and [14] :

Considering:

$$E_{arm} = N\frac{1}{2}C_{cell}V_{cell}^2 \quad (28)$$

According to articles [2] and [4] for MMC:

$$\left.\begin{array}{l} E_{arm}(\mathrm{t}) = \mathrm{n}\times \mathrm{E_{cell}} \\ \mathrm{E_{cell}} = \dfrac{C_{cell}}{2}V_{cell}^2(\mathrm{t}) \end{array}\right\} \rightarrow E_{arm}(\mathrm{t}) = \mathrm{n}\frac{C_{cell}}{2}V_{cell}^2(\mathrm{t})$$

Maximum energy deviation $\Delta\hat{\mathrm{E}}_{arm}$

Minimum energy deviation $\Delta\breve{\mathrm{E}}_{arm}$

Initial energy state $E_{arm}(0)$

$$\begin{cases} \mathrm{n}\dfrac{C_{cell}}{2}(\mathrm{V}_{cell_{nominal}}(1+\Delta V))^2 = E_{arm}(0) + \Delta\hat{\mathrm{E}}_{arm} \\ \mathrm{n}\dfrac{C_{cell}}{2}(\mathrm{V}_{cell_{nominal}}(1-\Delta V))^2 = E_{arm}(0) + \Delta\breve{\mathrm{E}}_{arm} \end{cases} \quad (29)$$

Then

$$\begin{cases} \mathrm{n}\dfrac{C_{cell}}{2}\mathrm{V}_{cell_{nominal}}^2 = \dfrac{E_{arm}(0) + \Delta\hat{\mathrm{E}}_{arm}}{(1+\Delta V)^2} \\ \mathrm{n}\dfrac{C_{cell}}{2}\mathrm{V}_{cell_{nominal}}^2 = \dfrac{E_{arm}(0) + \Delta\breve{\mathrm{E}}_{arm}}{(1-\Delta V)^2} \end{cases} \quad (30)$$

Then by subtracting

$$0 = \frac{E_{arm}(0) + \Delta\hat{\mathrm{E}}_{arm}}{(1+\Delta V)^2} - \frac{E_{arm}(0) + \Delta\breve{\mathrm{E}}_{arm}}{(1-\Delta V)^2} \quad (31)$$

Then

$$0 = \frac{E_{arm}(0) + \Delta\hat{\mathrm{E}}_{arm}}{(1+\Delta V)^2} - \frac{E_{arm}(0) + \Delta\breve{\mathrm{E}}_{arm}}{(1-\Delta V)^2} \rightarrow$$

$$0 = \frac{(E_{arm}(0) + \Delta\hat{\mathrm{E}}_{arm})(1-\Delta V)^2 - (E_{arm}(0) + \Delta\breve{\mathrm{E}}_{arm})(1+\Delta V)^2}{(1+\Delta V)^2(1-\Delta V)^2} \rightarrow$$

$$(E_{arm}(0) + \Delta\hat{\mathrm{E}}_{arm})(1-\Delta V)^2 - (E_{arm}(0) + \Delta\breve{\mathrm{E}}_{arm})(1+\Delta V)^2 = 0 \rightarrow$$

$$4\Delta VE_{arm}(0) = \Delta\hat{\mathrm{E}}_{arm}(1-\Delta V)^2 - \Delta\breve{\mathrm{E}}_{arm}(1+\Delta V)^2$$

Then

$$4\Delta VE_{arm}(0) = \Delta\hat{\mathrm{E}}_{arm}(1-\Delta V)^2 - \Delta\breve{\mathrm{E}}_{arm}(1+\Delta V)^2 \quad (32)$$

So

$$E_{arm}(0) = \frac{\Delta\hat{\mathrm{E}}_{arm}(1-\Delta V)^2 - \Delta\breve{\mathrm{E}}_{arm}(1+\Delta V)^2}{4\Delta V}$$

Considering:

$$\Delta\mathrm{E}_{arm} = \Delta\hat{\mathrm{E}}_{arm} - \Delta\breve{\mathrm{E}}_{arm} \quad (33)$$

$$\frac{n.C_{cell}}{2}\mathrm{V}_{cell_{nominal}}^2[(1+\Delta V)^2 - (1-\Delta V)^2] = \Delta\hat{\mathrm{E}}_{arm} - \Delta\breve{\mathrm{E}}_{arm}$$

$$\frac{n.C_{cell}}{2}\mathrm{V}_{cell_{nominal}}^2[(1+\Delta V)^2 - (1-\Delta V)^2] = \Delta\hat{\mathrm{E}}_{arm} - \Delta\breve{\mathrm{E}}_{arm}$$

$$\rightarrow \frac{n.C_{cell}}{2}\mathrm{V}_{cell_{nominal}}^2 .4\Delta V = \Delta\hat{\mathrm{E}}_{arm} - \Delta\breve{\mathrm{E}}_{arm}$$

$$.\frac{n.C_{cell}}{2}\mathrm{V}_{cell_{nominal}}^2 .4\Delta V = \Delta E_{arm} \quad (34)$$

$$\frac{n.C_{cell}}{2} \mathrm{V}^2_{cell_{nominal}} = E_{arm_{nominal}} \quad (35)$$

Then

$$E_{arm_{nominal}}.4\Delta V = \Delta E_{arm} \quad (36)$$

Then

$$\rightarrow \Delta E_{arm} = E_{arm_{nominal}}.4\Delta V \quad (37)$$

$$\rightarrow E_{arm_{nominal}} = \frac{\Delta E_{arm}}{4\Delta V} \quad (38)$$

Then

$$\left.\begin{aligned} E_{arm}(\mathrm{t}) &= \mathrm{n}\frac{C_{cell}}{2} V^2_{cell}(\mathrm{t}) \\ E_{arm_{nominal}} &= \frac{\Delta E_{arm}}{4\Delta V} \end{aligned}\right\} \rightarrow C_{cell} = \frac{E_{u,j}}{2.n.V^2_{cell_{nominal}}.\Delta v} \quad (39)$$

In conclusion:

$$C_{cell} = \frac{E_{u,j}}{2.n.V^2_{cell_{nominal}}.\Delta v} \quad (40)$$

3. INDUCTANCE SELECTION

Inductor calculation is based on [6].

First based on (25) common mode energy between upper and lower arms is defined as:

$$E_{CM,j} \square \left(E_{u,j} + E_{l,j}\right) = 2 \times \frac{P_{dc}}{4\omega} \frac{\sin(2\omega t + \varphi)}{2.\cos\varphi} = \frac{P_{dc}}{4\omega} \frac{\sin(2\omega t + \varphi)}{\cos\varphi} \quad (48)$$

Then:

$$E_{CM,j} = \frac{P_s}{4\omega} \sin(2\omega t + \varphi) \quad (49)$$

With considering double fundamental frequency component in the arms voltage:

$$\begin{cases} v_{u,j} = \dfrac{V_{dc}}{2}(1 - m\sin\omega t) + \dfrac{U_{2f}}{2}\sin\left(2\omega t + \varphi\right) \\ v_{l,j} = \dfrac{V_{dc}}{2}(1 + m\sin\omega t) + \dfrac{U_{2f}}{2}\sin\left(2\omega t + \varphi\right) \end{cases} \quad (50)$$

This double fundamental frequency voltage creates circulating current following through two arm inductors.

$$v(\mathrm{t}) = L\frac{di}{dt} \rightarrow i = \frac{1}{L}\int v(\mathrm{t})dt \quad (51)$$

Then:

$$i_{2f} = \frac{1}{L}\int v(\mathrm{t})dt = \frac{1}{L}\int \frac{U_{2f}}{2}\sin\left(2\omega t + \varphi\right)dt =$$
$$= \frac{U_{2f}}{2L}\left(\frac{-\cos\left(2\omega t + \varphi\right)}{2\omega}\right) = -\frac{U_{2f}}{4L\omega}\cos\left(2\omega t + \varphi\right) \quad (52)$$

And peak value of circulating current will be:

$$I_{2f} = -\frac{U_{2f}}{4L\omega} \quad (41)$$

Then

$$i_{2f} = -\frac{U_{2f}}{4L\omega}\cos\left(2\omega t + \varphi\right) = I_{2f}\cos\left(2\omega t + \varphi\right) \quad (53)$$

So, the arm currents will be

$$\begin{cases} i_{u,j} = \dfrac{i_{dc}}{2}[1 + k\sin(\omega t + \varphi)] + I_{2f}\cos\left(2\omega t + \varphi\right) \\ i_{l,j} = \dfrac{i_{dc}}{2}[1 - k\sin(\omega t + \varphi)] + I_{2f}\cos\left(2\omega t + \varphi\right) \end{cases} \quad (54)$$

Then by integrating instantaneous power in phase,

the common mode energy should be edited.

$$P_{CM} = \left[\frac{P_s}{2}\cos(2\omega t + \varphi)\right] + \begin{bmatrix} 2\dfrac{U_{2f}}{2}\sin(2\omega t + \varphi) \times \dfrac{1}{2}i_{dc} + \\ 2\dfrac{U_{2f}}{2}\sin(2\omega t + \varphi) \times I_{2f}\cos\left(2\omega t + \varphi\right) \\ +2\dfrac{1}{2}V_{dc}I_{2f}\cos\left(2\omega t + \varphi\right) \end{bmatrix} \quad (55)$$

Then

$$P_{CM} = \left[\frac{P_s}{2}\cos(2\omega t + \varphi)\right] + \begin{bmatrix} \dfrac{U_{2f}i_{dc}}{2}\sin(2\omega t + \varphi) + \\ \dfrac{U_{2f}I_{2f}}{1}\left[\dfrac{1}{2}\left(\sin(4\omega t + 2\varphi) + \sin(0)\right)\right] \\ +V_{dc}I_{2f}\cos\left(2\omega t + \varphi\right) \end{bmatrix} \quad (56)$$

$$E = \int P \quad (57)$$

Then

$$E_{CM} = \left[\frac{P_s}{4\omega}\sin(2\omega t + \varphi)\right] + \begin{bmatrix} -\dfrac{U_{2f}i_{dc}}{2 \times 2\omega}Cos(2\omega t + \varphi) + \\ -\dfrac{U_{2f}I_{2f}}{2 \times 4\omega}\left[\left(\cos(4\omega t + 2\varphi)\right)\right] \\ +\dfrac{V_{dc}I_{2f}}{2\omega}\sin\left(2\omega t + \varphi\right) \end{bmatrix} \quad (58)$$

With considering just the peak value of circulating current, then:

$$I_{2f} = \frac{U_{2f}}{4L\omega} \tag{59}$$

Then

$$E_{CM} = \left[\frac{P_s}{4\omega}\sin(2\omega t+\varphi)\right] + \begin{bmatrix} -\frac{U_{2f} i_{dc}}{4\omega} Cos(2\omega t+\varphi) + \\ -\frac{U_{2f}^2}{8\omega \times 4\omega L}\left[\left(\cos(4\omega t+2\varphi)\right)\right] \\ +\frac{V_{dc} U_{2f}}{2\omega \times 4\omega L}\sin\left(2\omega t+\varphi\right) \end{bmatrix} \tag{60}$$

Finally:

$$E_{CM} = \left[\frac{P_s}{4\omega}\sin(2\omega t+\varphi)\right] + \begin{bmatrix} -\frac{U_{2f} i_{dc}}{4\omega} Cos(2\omega t+\varphi) + \\ -\frac{U_{2f}^2}{32\omega^2 L}\left[\left(\cos(4\omega t+2\varphi)\right)\right] \\ +\frac{V_{dc} U_{2f}}{8\omega^2 L}\sin\left(2\omega t+\varphi\right) \end{bmatrix} \tag{61}$$

To make it comparable with [6]:

$$E_{CM} = \left[\frac{P_s}{4\omega}\sin(2\omega t+\varphi)\right] + \begin{bmatrix} +\frac{V_{dc} U_{2f}}{8\omega^2 L}\sin\left(2\omega t+\varphi\right) \\ -\frac{U_{2f} i_{dc}}{4\omega} Cos(2\omega t+\varphi) + \\ -\frac{U_{2f}^2}{32\omega^2 L}\cos(4\omega t+2\varphi) \end{bmatrix} \tag{62}$$

Third and fourth terms can be neglected compare to second term [6], then

$$E_{CM} \approx \left[\frac{P_s}{4\omega} + \frac{V_{dc} U_{2f}}{8\omega^2 L}\right]\sin\left(2\omega t+\varphi\right) \tag{63}$$

Double fundamental frequency voltage U_{2f} will distribute evenly among 2N cell in steady state situation. Then submodule capacitor voltage become:

$$u_c(\mathrm{t}) = U_c + \frac{U_{2f}}{2.N}\sin\left(2\omega t+\varphi\right) \tag{64}$$

where Uc is the dc component of the capacitor voltage.

$$U_c = \frac{V_{dc}}{N} \tag{65}$$

N is the number of submodules per arm. Thus, the total energy stored in the phase unit j can be calculated as:

$$E_{\mathrm{phase},j} = 2 \times N \times \frac{1}{2} \times C_0 \times u_c^2(\mathrm{t}) = N C_0 u_c^2(\mathrm{t}) \tag{66}$$

With substituting:

$$E_{\mathrm{phase},j} = N \times C_0 \times U_c^2 + C_0 U_c U_{2f}\sin\left(2\omega t+\varphi\right) + \frac{C_0 U_{2f}^2}{4.N}\sin^2\left(2\omega t+\varphi\right) \tag{67}$$

Comparing:

$$\begin{cases} E_{CM} \approx \left[\frac{P_s}{4\omega} + \frac{V_{dc} U_{2f}}{8\omega^2 L}\right]\sin\left(2\omega t+\varphi\right) \\ E_{\mathrm{phase},j} = N \times C_0 \times U_c^2 + C_0 U_c U_{2f}\sin\left(2\omega t+\varphi\right) + \frac{C_0 U_{2f}^2}{4.N}\sin^2\left(2\omega t+\varphi\right) \end{cases} \tag{68}$$

The double fundamental frequency component should be equal to second term in phase energy:

$$\frac{P_s}{4\omega} + \frac{V_{dc} U_{2f}}{8\omega^2 L} = C_0 U_c U_{2f} \tag{69}$$

Thus:

$$U_{2f} = \frac{P_s}{4\omega} \Big/ \left(C_0 U_c - \frac{V_{dc}}{8\omega^2 L}\right) \tag{70}$$

Then from (70):

$$I_{2f} = \frac{U_{2f}}{4L\omega} = \frac{\frac{P_s}{4\omega} \Big/ \left(C_0 U_c - \frac{V_{dc}}{8\omega^2 L}\right)}{4L\omega}$$
$$= P_s \frac{1}{16L\omega^2}\frac{1}{\left(C_0 U_c - \frac{V_{dc}}{8\omega^2 L}\right)} = \frac{P_s}{2}\frac{1}{\left(8\omega^2 L C_0 U_c - V_{dc}\right)} \tag{71}$$

To derive x(t), differential equations with time varying coefficients should be solved. Then, x(t) is used to calculate currents and voltages of the PESs in normal condition [15]. Based on the proposed method in [16] to identify an AOV to voltage sag in case of SPG fault occurrence, the first principle to design the parameter of the arm inductor at a given circulating current peak value can be derived as:

$$L = \frac{1}{8\omega^2 C_0 U_c}\left(\frac{P_s}{2I_{2f}} + V_{dc}\right) \tag{72}$$

4. CONCLUSION

In this paper the high-power inverter parameter selection procedure has been proposed. The method involves two steps. The first step is devoted to arm capacitance selection, which depends on the rated converter power and its voltage, and the second step is devoted to inductance selection.

5. REFERENCES

[1] Nami, A., Liang, J., Dijkhuizen, F., & Demetriades, G. D. (2014). Modular multilevel converters for HVDC applications: Review on converter cells and functionalities. *IEEE Transactions on Power Electronics*, *30*(1), 18-36.

[2] Wang, M., Hu, Y., Zhao, W., Wang, Y., & Chen, G. (2016). Application of modular multilevel converter in medium voltage high power permanent magnet synchronous generator wind energy conversion systems. *IET Renewable Power Generation*, *10*(6), 824-833.

[3] Li, Z., Pei, Y., Wang, L., Zhao, L., Pei, L., & Cao, W. (2023). A Comprehensive Closed-Loop Voltage Ripple Control Scheme for Modular Multilevel Converter-Based Power Electronic Transformers. *IEEE Transactions on Power Electronics*.

[4] Rong, F., Gong, X., & Huang, S. (2016). A novel grid-connected PV system based on MMC to get the

maximum power under partial shading conditions. *IEEE Transactions on Power Electronics*, *32*(6), 4320-4333.

[5] Vasiladiotis, M., & Rufer, A. (2014). Analysis and control of modular multilevel converters with integrated battery energy storage. *IEEE Transactions on Power Electronics*, *30*(1), 163-175.

[6] Naghizadeh, M., Farjah, E., & Ghanbari, T. (2019). DC microgrid grounding impact on power electronic interfaces in fault condition. *IEEE Transactions on Industrial Electronics*, *67*(5), 4120-4132.

[7] Ranjram, M., & Lehn, P. W. (2015). A multiport power-flow controller for DC transmission grids. *IEEE Transactions on Power Delivery*, *31*(1), 389-396.

[8] Naghizadeh, M., Farjah, E., Samet, H., & Ghanbari, T. (2018, June). Fault tolerability of power electronic interfaces, impact of grounding architecture. In *2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe)* (pp. 1-6). IEEE.

[9] Naghizadeh, M., Farjah, E., Ghanbari, T., Pourgharibshahi, H., & Andani, M. T. (2018, September). Efficient grounding method for DC microgrid with multiple grounding points. In *2018 Clemson University Power Systems Conference (PSC)* (pp. 1-6). IEEE.

[10] Ruan, X. (2014). *Soft-switching PWM full-bridge converters: topologies, control, and design*. John Wiley & Sons.

[11] Naghizadeh, M., Gohari, H. S., Hojabri, H., & Muljadi, E. (2022). New single–phase three-wire interlinking converter and hybrid AC/LVDC microgrid. *IEEE Transactions on Power Electronics*, *38*(4), 4451-4463.

[12] Naghizadeh, M., Hojabri, H., & Muljadi, E. (2023). A Common-Grounded Single-Phase AC/Bipolar DC Hybrid Microgrid with a Four-Leg Interlinking Converter. *IEEE Journal of Emerging and Selected Topics in Power Electronics*.

[13] Tu, Q., Xu, Z., & Xu, L. (2011). Reduced switching-frequency modulation and circulating current suppression for modular multilevel converters. *IEEE transactions on power delivery*, *26*(3), 2009-2017.

[14] Merlin, M. M., & Green, T. C. (2015). Cell capacitor sizing in multilevel converters: cases of the modular multilevel converter and alternate arm converter. *IET Power Electronics*, *8*(3), 350-360.

[15] Naghizadeh, M., Farjah, E., Ghanbari, T., & Muljadi, E. (2023, February). Impact of Grounding Conditions on Power Electronic Interfaces in a DC Microgrid. In *2023 IEEE Texas Power and Energy Conference (TPEC)* (pp. 1-6). IEEE.

[16] Shakeri, S., Naghizadeh, M., & Esmaeili, S. (2020, August). Identifying the voltage sags vulnerability area with considering FACTS devices. In *2020 28th Iranian conference on electrical engineering (ICEE)* (pp. 1-5). IEEE.