MŰEGYETEM 1782

Budapest University of Technology and Economics

Department of Automation and Applied Informatics

New Five-Level, Four-Channel, Resonant Buck Converter

Új ötszintű, négycsatornás rezonáns Buck konverter

PhD Thesis Booklet

Lilla Litváni

Supervisor: János Hamar, PhD

2020

1 Motivation and Background

DC-DC converters are used widely in the world at several application fields such as telecommunication, server, storage and network, industrial robotics, aerospace, medical, automotive etc. Currently, DC-DC converter market is worth 8.5 billion USD and is expected to grow to 22.4 billion USD by 2025. Due to this relevant growth in the market, cost-effective, high performance models are needed [1].

In DC nano - or microgrids consumers, sources and control entities operating at different voltage levels can be connected by multilevel converters. The latter is more cost-effective and economical from the hardver point of view, however its control is more complicated. In these systems an uninterruptible power flow is a key factor to provide a secure power supply for the loads, while loss minimization is also very important to maximize efficiency. In DC nanogrids several inverters can occur feeding AC consumers. These inject further harmonics to the DC grid which are important to reduce. These harmonics can be reduced by an appropriate multilevel converter that provides multiple output voltages. As in these systems the power of each load might change, a specific strategy is required to control the power flow among the output channels of the converter. To meet all of these goals and properly suit these applications, a special DC-DC converter is needed. The aim of my research is to design the main circuit and elaborate the control of a special multilevel DC-DC converter that consists of multiple outputs at a minimized number of switches.

In this dissertation a new five level, four channel DC-DC converter is proposed that can be suitable for the previously mentioned application areas. The converter provides five voltage levels and has two input channels. Might one of the inputs fall out or the available power level decrease, the other input channel can take its role thus providing an uninterruptible power supply for the consumers.

The proposed converter has six controlled semiconductor switches in the channels. They are needed to control the power flow among the two input and four output channels as during operation both the input and output power can change. Clarification of the operation of the new converter is based on a detailed steady state analysis which is the subject of the first contribution. Having two different input sources (e.g. a battery and a solar cell), might the voltage of one of the inputs decrease, a special control strategy is needed to provide the required output voltages for the consumers.

From an operation point of view two cases might occur. Symmetrical operation is typical in simpler cases, when input and output voltages, and loads are equal respectively. In the second contribution, I examined the effect of several control parameters on the converter operation in case of a symmetrical operation.

In practise, asymmetrical operation is more highly likely. In the third contribution I first analysed the partially asymmetrical situations, such as asymmetrical input or output voltages or asymmetrical loads. Afterwards, I generalized the analysis for the fully asymmetrical operation cases. In my research a special power flow control was proposed for both partially and fully asymmetrical operation of the converter. Finally, I identified the possible operational domains of the converter, and I defined the operational conditions in the different domains, which I also analysed for several scenarios. Theoretical results were supported by both simulations and experiments in all cases which confirmed the results of the analysis.

2 State of the Art

In recent trends, various kinds of converters, special semiconductor elements and new control methods have been proposed that are suitable for renewable energy systems, multilevel inverter drives and other applications .The main goals of these research activities are the reduction of switching stresses and losses, improvement of the efficiency, and lessening of the number of elements in the circuit and also the electromagnetic interference (EMI) [2].

Two level DC-DC and DC-AC converters are appropriate for low power and low voltage applications in which harmonic distortion can be significant causing several problems. Although the unwanted harmonic distortion can be eliminated by adding passive filters specified for the harmonic orders, this solution increases both the size, weight and the cost of the converter. Increasing the switching frequency can reduce both the size of the converter and the amplitude of the harmonics, however this also leads to the decrease of the semiconductor switching time. At an unchanged supply voltage, this can increase the voltage slope, thus increasing the radiated noises as well. Using a special, resonant DC-DC converter, it is possible to decrease the distortion and the magnetic losses even at a 1 MHz switching frequency [3].

Harmonic elements can also be decreased by using multilevel converters without applying costly filters or operating at very high switching frequency. On the other hand, the disadvantage of these converters can be the complexity of topology, the excessive number of switching devices and the increased switching losses. Thus, the main goal is to develop multilevel converters that are less complex and expensive, but reliable and highly efficient. There are several existing topologies of these converters, among others the neutral point clamped (NPC) converters, flying capacitor converters (FCC) and also the cascaded H-bridge converters (CHB) [4]. Several CHB topologies have been proposed that are capable of reducing the amount of switching elements. Multilevel topologies with a level doubling network can allow a wider number of output voltages [5]. Minimized number of power electronic switches made the output of multiple voltage levels possible with several novel cascade switched-diode, symmetric and asymmetric converter topologies in [6]. An asymmetrical cascade multilevel converter was proposed consisting of submultilevel converter blocks that generated several voltage levels, while also reduced the number of DC sources and switching elements, losses and the costs of the converter [7].

T-type converters are an advance type of NPC topologies which compared to traditional NPCs allowed a reduced number of switches and higher efficiency. Three-level T-type converters combine the advantages of two-level converters (e.g. simple operation principle, reduced conduction losses) with the positive sides of three-level topologies (e.g. high output voltage quality, reduced switching losses) [8].

Another option to increase the number of voltage levels is to use a transformer-based modular converter, which however also increases the complexity of the circuit. A family of bidirectional, non-isolated, magnetic coupling DC-DC converters were presented to achieve soft-switching with a simple circuit allowing both low cost and high efficiency at the same time [9]. Five-level LLC resonant converter is introduced consisting of main/auxiliary transformers, two three-level bridge arms, a set of rectifier bridge and also several resonant elements. Applying various modulation methods, the converter can operate with low, medium and high voltage gains as well [10].

The proposed converter types, however each have their drawbacks. Modular models require large and expensive isolated transformers. Neutral point clamped converters have no self-balancing feature and the increase of levels goes with the rising number of clamping diodes. Flying capacitor multi-cell converters require large and high-priced DC capacitors. T-type converters require a complex capacitor balancing technique, and also the open-circuit voltage on the upper and lower switches are higher compared to the clamping switches. Furthermore, modified cascade-H-bridge converters can reduce the number of semiconductor devices however, isolated DC sources are required [4].

The four channel resonant Buck converter presented in my thesis on the other hand implements the advantages of the presented converters, allowing four controllable output voltage levels during operation, which can be delivered even when the input voltage or power changes. Furthermore, this converter makes both zero voltage and zero current switching (ZVS and ZCS) possible, thus lowering switching losses and increasing the efficiency.

3 New Scientific Results

In this section, contributions of the current dissertation are presented in detail. The new results are grouped into three theses, which are discussed in the following sections.

Thesis I

I proposed a new, five level, four channel resonant Buck converter topology that allows the precise control of each output voltage and the increase of the efficiency by both ZVS and ZCS, combining the advantages of the currently used DC-DC converters (Figure 1).

I examined the four-four switching states for both the positive and negative channels, and depicted the corresponding voltage and current waveforms (Figure 2). *I prepared a detailed steady state analysis for both discontinuous and continuous current conduction modes of the converter (*(1) (2) (3) (4)*).* [j1] [p1].

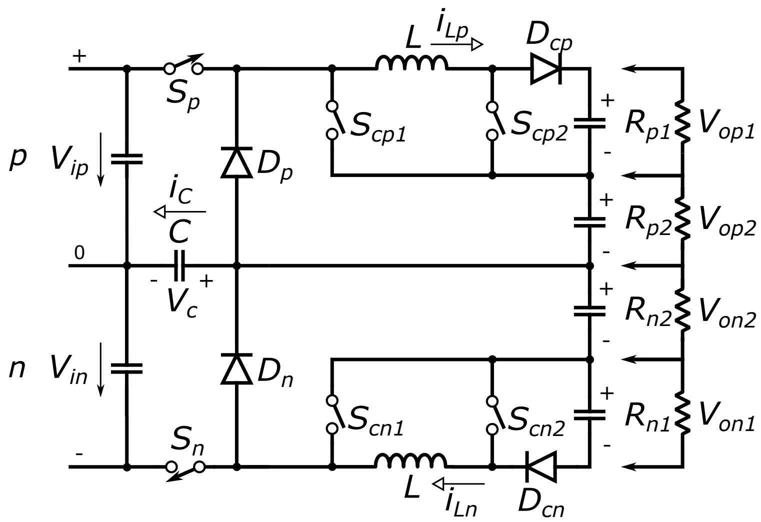

Figure 1: Main Circuit of the Five Level Four Channel Resonant Buck Converter [j1]

The converter can produce five voltage levels: zero and four equal or completely different voltages. I examined the possible switching states for both channels, furthermore I also depicted the corresponding voltage and current waveforms which can be seen in Figure 2.

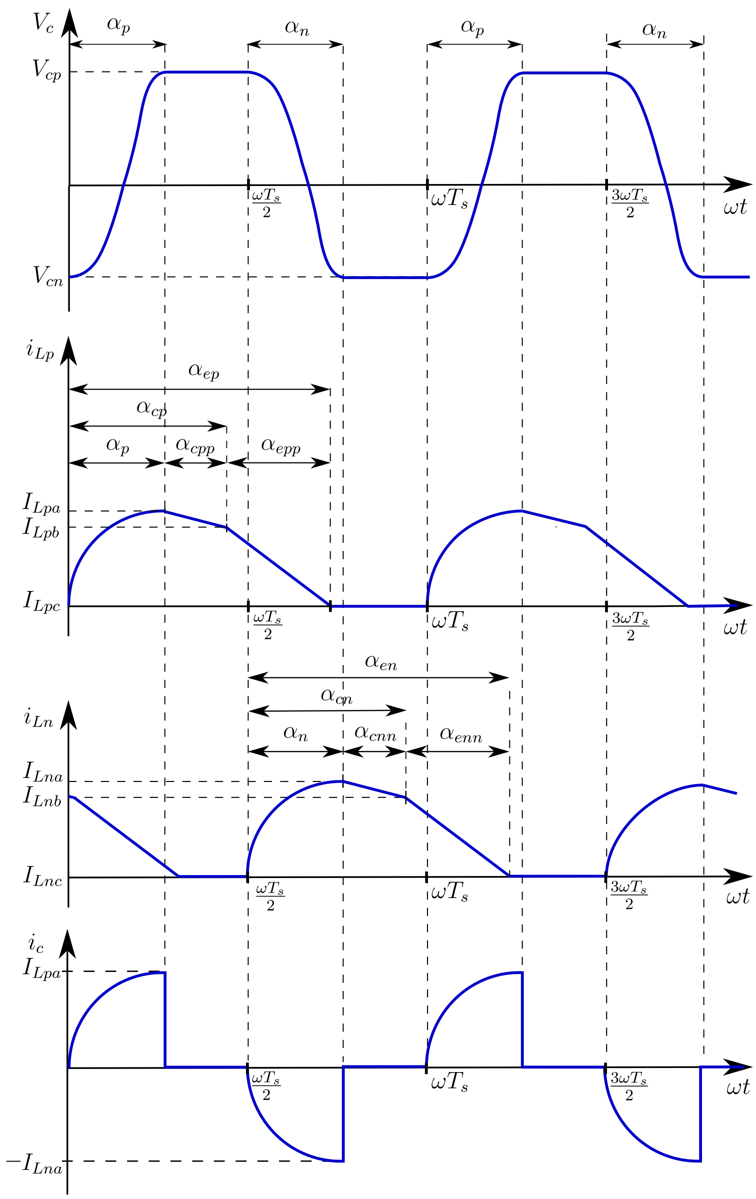

Figure 2: Steady State Operating Waveforms of Time Functions in DCM[j1]

I defined the dependence of output voltages on both the circuit and control parameters in continuous (CCM) and discontinuous (DCM) current conduction mode. These can be described in the followings. In continuous current conduction mode the output voltages can be calculated as:

$$V_{op1,CCM} = K_{15p} \cdot \frac{4Cf_sV_{i1}}{\frac{K_{14p}^2}{R_{p2}} + \frac{K_{15p}^2}{R_{p1}} + \frac{K_{14n}^2}{R_{n2}} + \frac{K_{15n}^2}{R_{n1}}} \tag{1}$$

$$V_{op2,CCM} = K_{14p} \cdot \frac{4Cf_sV_{i1}}{\frac{K_{14p}^2}{R_{p2}} + \frac{K_{15p}^2}{R_{p1}} + \frac{K_{14n}^2}{R_{n2}} + \frac{K_{15n}^2}{R_{n1}}} \tag{2}$$

where $V_{i1} = \frac{V_{ip}+V_{in}}{2}$, f_s is the switching frequency, K_{14p}, K_{15p} parameters can be calculated based on the $A.16 - A.17$ equations on page 119. in the Appendix A2. of the thesis. Corresponding n channel equations can be based on the p channel equations, with formal parameter substitutions.

In discontinuous current conduction mode the output voltages can be calculated as follows:

$$V_{op1,DCM} = K_{1p} \cdot \frac{4Cf_sV_{i1}}{\frac{K_{1p}^2}{R_{p1}} + \frac{K_{2p}^2}{R_{p2}} + \frac{K_{1n}^2}{R_{n1}} + \frac{K_{2n}^2}{R_{n2}}} \tag{3}$$

$$V_{op2,DCM} = K_{2p} \cdot \frac{4Cf_sV_{i1}}{\frac{K_{1p}^2}{R_{p1}} + \frac{K_{2p}^2}{R_{p2}} + \frac{K_{1n}^2}{R_{n1}} + \frac{K_{2n}^2}{R_{n2}}} \tag{4}$$

where parameters K_{1p} and K_{2p} can be calculated based on the $A.1 - A.3$ equations on page 118. in the Appendix A1. of the thesis.

I verified the theoretical results by both simulations and laboratory measurements on an experimental prototype which can be found in Section 3.3 on page 25-31. in the thesis.

Thesis II

I elaborated control strategies of the five level, four channel resonant Buck converter for symmetrical input and output voltages and equal loads.

In my research, I investigated the individual and joint effect on the output voltages and converter operation of three control variables: the turn-off time instant of the primarily controlled semiconductor switch, the switching frequency, and the switched capacitor peak voltage. [j1] [p1]

I identified the different operational domains of the converter, both the continuous and discontinuous current conduction mode and also limitations of the resonant capacitor voltage. In these operation modes, the output voltage can be calculated based on the following equations:

$$V_{o,CCM}^{*,symm} = \frac{1}{1 + \frac{\cot\frac{\alpha}{2}}{4}\left(-\alpha + \frac{2\pi}{f_s^*}\right)} \tag{5}$$

$$V_{o,DCM}^{*,symm} = \sqrt{\frac{R^{*2} f_s^{*2}}{\pi^2}\tan^4\frac{\alpha}{2} + \frac{2R^* f_s^*}{\pi}\tan^2\frac{\alpha}{2}} - \frac{R^* f_s^*}{\pi}\tan^2\frac{\alpha}{2} \tag{6}$$

$$V_{o,prot,CCM}^{*,symm} = \frac{2\left(\cos(2\alpha) + \frac{1}{1+\cos\alpha} - 2 \pm \sqrt{(\cos(2\alpha) + \frac{1}{1+\cos\alpha} - 2)^2 - \tan^2\frac{\alpha}{2}\cot^2\alpha}\right)}{\tan^2\frac{\alpha}{2}} \tag{7}$$

where R^* is the load resistance, f_s^* is the switching frequency in per unit, α is the switching angle of the primarily controlled semiconductor switch.

As the analysis lead to complicated equations, first I examined the effect on the output voltage of the switching frequency and the switching angle of the primarily controlled semiconductor switch. The results can be seen in the following figure (Figure 3).

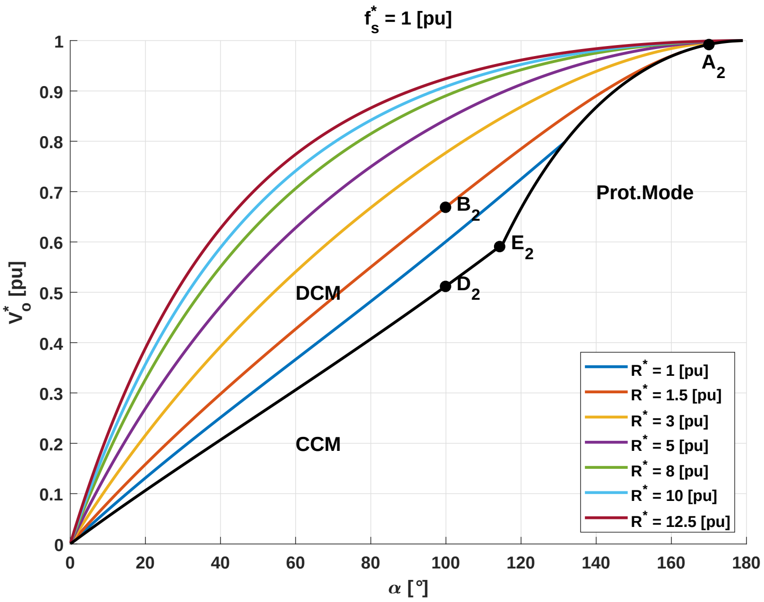

Figure 3: Control Characteristics of Output Voltage V_o^* in the function of switching angle α and load resistance R^*, where switching frequency equals to the resonant frequency, $f_s^* = 1$ [j1]

I supported the theoretical results by both simulations and laboratory measurements which can be found on pages 51-54. in section 4.3 in the thesis.

In the next step, I examined the effect of the switching frequency and the resonant capacitor peak voltage on the output voltage. The results can be seen in the next figure (Figure 4).

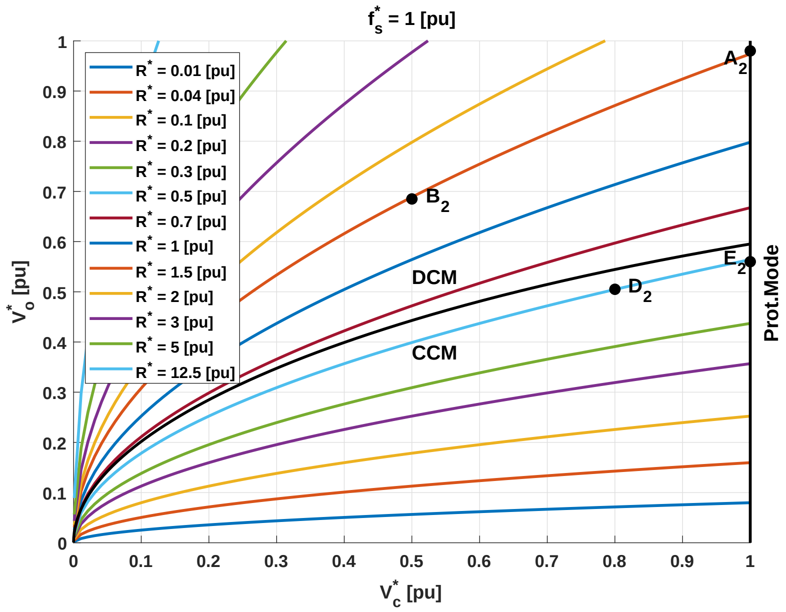

Figure 4: Control Characteristics of Output Voltage V_o^* in the function of the resonant capacitor voltage, V_c^* and load resistance R^*, where switching frequency equals to the resonant frequency, $f_s^* = 1$ [j1]

I supported the theoretical results by both simulations and laboratory experiments, which can be found on pages 51-54. in section 4.3 in the thesis.

Based on the theoretical and experimental results, it can be concluded that controlling the converter by the resonant capacitor voltage, the voltage of the semiconductor switches and thus indirectly the efficiency of the converter can be affected. On the other hand a more complex control is needed in order to maintain the output voltages. Controlling the converter by the turn-off time of the primarily controlled semiconductor switch, duty ratios of the semiconductor switches can be calculated directly. This makes the actuation much simpler, however maintaining the operational voltage of the resonant capacitor becomes more complex.

Thesis III

I carried out a new, energy pulse equation based steady state analysis of the five level, four channel Buck converter which allows the determination of the power transferred through the converter and its exchange among the input and output channels at every operational cases and load profiles. [j2] [p2] [j3]

Considering the voltage of the two input and four output channels and loads, output voltages of the converter based on the energy equation method can be calculated in the following way in continuous and discontinuous current conduction mode.

$$V_{op2,CCM} = \frac{Z(I_{Lpc} - I_{Lpb})}{\alpha_p - \frac{Z}{V_{op1}}(I_{Lpb} - I_{Lpa}) - \omega T_s} \tag{8}$$

$$V_{op1,CCM} = V_{ip} + V_{c1} - V_{c2} - V_{op2,CCM} - \frac{2V_{c1} - I_{Lpc} Z \sin \alpha_p}{1 - cos\alpha_p} \tag{9}$$

$$V_{op2,DCM} = R_{p2} f_s C V_{c1} \left(1 + \sqrt{1 + \frac{L I_{Lpb}^2}{2 R_{p2} f_s C^2 V_{c1}^2}}\right) \tag{10}$$

$$V_{op1,DCM} = \sqrt{2 C V_{c1} R_{p1} f_s \left(V_{ip} - V_{c2} - V_{op2,DCM} - \frac{1}{2} L I_{Lpb}^2 R_{p1} f_s\right)} \tag{11}$$

where $V_{c1} = \frac{V_{cp} - V_{cn}}{2}$ and $V_{c2} = \frac{V_{cp} + V_{cn}}{2}$ are the voltages of the resonant capacitor, $Z = \sqrt{\frac{L}{C}}$ is the characteristic impedance, $\omega = \frac{1}{\sqrt{LC}}$, I_{Lpa}, I_{Lpb}, and I_{Lpc} are the instantaneous values of the inductor current at the turn off time of the primarily, secondarily and thirdly controlled semiconductor switches S_p, S_{cp1}, and S_{cp2} respectively. Corresponding channel n equations can be written based on the channel p equations, with formal parameter substitutions.

Based on this new method I proved, that the total power transferred through the converter is determined by the difference of the positive and negative switched capacitor peak voltages, the power exchange among input channels is set by the sum of the positive and negative switched capacitor peak voltages. I also showed that the power exchange among the output channels on both sides is determined by the instantaneous values of the inductor currents at the turn off times of the secondarily controlled semiconductor switches S_{cp1} and S_{cn1}. I established the borders of the continuous and discontinuous current conduction modes and also the limitations of the voltage of the resonant capacitor and the inductor current, which determine the operational domains of the converter.

I proposed power flow control strategies for both symmetrical and asymmetrical operations in continuous and discontinuous current conduction modes based on these results which can be seen in Table 1. The full description of the control method can be found in section 5.2. on pages 71-85. in my thesis.

Table 1: Adjustment of Control Variables in Specified Asymmetrical Cases (when output $p-n$ channels are symmetrical) [j2]

Input Voltage		Output Voltage		Loads		Control			
V_{ip}	V_{in}	V_{op1}	V_{op2}	R_{p1}	R_{p2}	V_{c1}	V_{c2}	I_{Lpb}	Operation Points
Symmetrical $V_{ip} = V_{in}$		Symmetrical $V_{op1} = V_{op2}$		↑	const.	↓	0	↑	$C_3 \to D_3$
				const.	↑	↓	0	↓	$C_3 \to E_3$
		↑	const.	Symmetrical $R_{p1} = R_{p2}$		↑	0	↓	$R_3 \to I_3$
		const.	↑			↑	0	↑	$I_3 \to H_3$

The new method allowed to control the converter by five parameters - the difference of the positive and negative peak resonant capacitor voltages, the sum of the positive and negative peak resonant capacitor voltages, and the instantaneous values of the inductor currents at the turn off times of the secondarily controlled semiconductor switches S_{cp1} and S_{cn1} - in all operational cases. The dependence of the output voltage on the inductor current and the resonant capacitor voltage can be seen in Figure 5 and Figure 6. (The full description of the control method can be seen in section 5.2. on pages 71-85. in my thesis.)

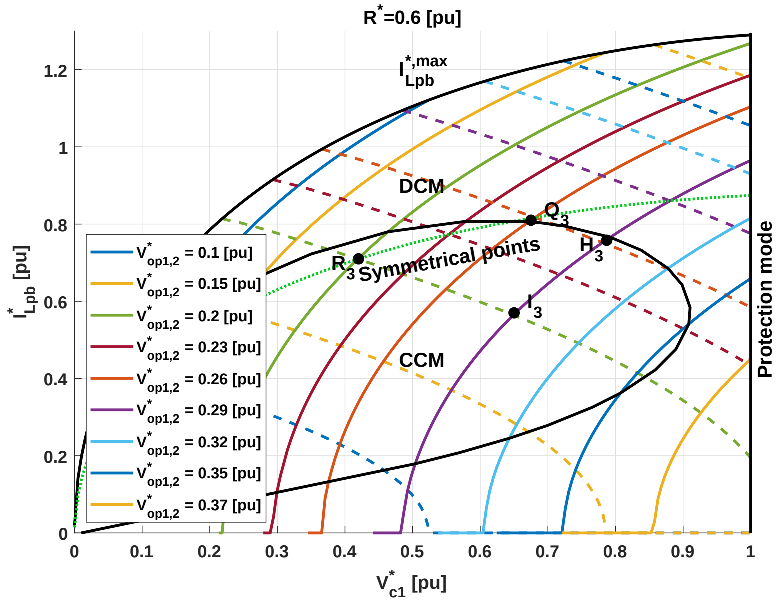

Figure 5: Control Characteristics of output voltage $V^*_{op1,2}$ in the function of capacitor voltage, V^*_{c1} and inductor current I^*_{Lpb}), where the load resistance is $R^* = 0.6$ [j2]

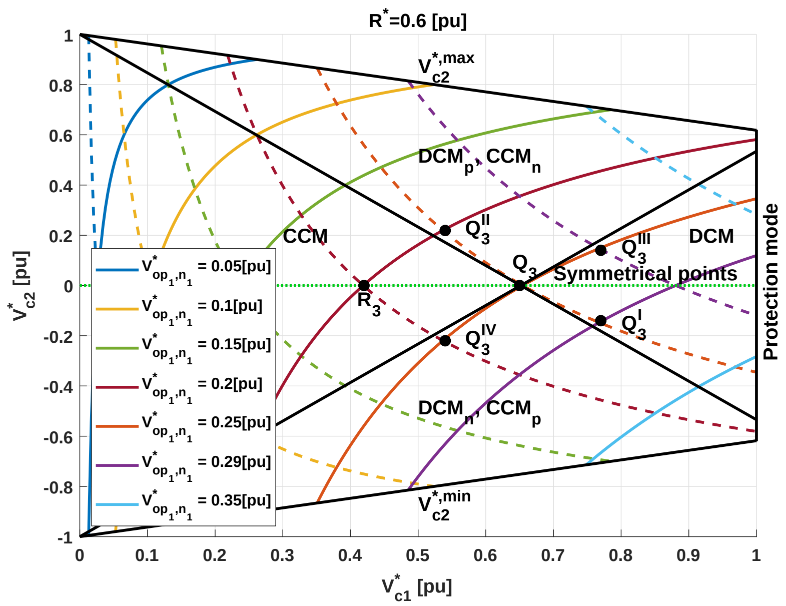

Figure 6: Control Characteristics of output voltage $V^*_{op1,n1}$ in the function of capacitor voltages V^*_{c1}, V^*_{c2}, where the load resistance is $R^* = 0.6$ [j3]

I confirmed the theoretical considerations by both simulations and laboratory experiments which can be found on pages 85-93. in my thesis, in section 5.3.

Bibliography

[1] Markets and Markets. *DC-DC Converter Market Forecast to 2025*. 2019. URL: https://www.marketsandmarkets.com/Market-Reports/global-dc-dc-converter-market-17565254.html.

[2] Janos Hamar and Istvan Nagy. "Control features of dual-channel DC-DC converters". In: *IEEE Transactions on Industrial Electronics* 49.6 (2002), pp. 1293–1305. ISSN: 0278-0046. DOI: 10.1109/TIE.2002.804981.

[3] Yueshi Guan, Yijie Wang, and Wei Wang et al. "A High-Frequency CLCL Converter Based on Leakage Inductance and Variable Width Winding Planar Magnetics". In: *IEEE Transactions on Industrial Electronics* 65 (1 2018), pp. 280–290. ISSN: 1557-9948. DOI: 10.1109/TIE.2017.2716878.

[4] A. Salem and M. A. Abido. "T-Type Multilevel Converter Topologies: A Comprehensive Review". In: *Arabian Journal for Science and Engineering* 44 (3 2018), 1713 – 1735. ISSN: 2191-4281. DOI: 10.1007/s13369-018-3506-6.

[5] Mohammad Mousavi, Younes Sangsefidi, and Ali Mehrizi-Sani et al. "Generalized Step-Down Switched-Capacitor Converter Under ZCS for Photovoltaic Applications". In: *IEEE Transactions on Energy Conversion* 33 (3 2018), pp. 1321–1329. ISSN: 1558-0059. DOI: 10.1109/TEC.2018.2815526.

[6] Rasoul Shalchi Alishah, Daryoosh Nazarpour, Seyed Hossein Hosseini, and Mehran Sabahi. "Novel Topologies for Symmetric, Asymmetric, and Cascade Switched-Diode Multilevel Converter With Minimum Number of Power Electronic Components". In: *IEEE Transactions on Industrial Electronics* 61 (10 2014), pp. 5300–5310. ISSN: 1557-9948. DOI: 10.1109/TIE.2013.2297300.

[7] E. Babaei, S.H. Hosseini, G.B. Gharehpetian, M. Tarafdar Haquea, and M. Sabahi. "Reduction of dc voltage sources and switches in asymmetrical multilevel converters using a novel topology". In: *Electric Power Systems Research* 77 (8 2007), pp. 1073–1085. ISSN: 0378-7796. DOI: 10.1016/j.epsr.2006.09.012.

[8] Mario Schweizer and Johann W. Kolar. "Design and Implementation of a Highly Efficient Three-Level T-Type Converter for Low-Voltage Applications". In: *IEEE*

Transactions on Power Electronics 28 (2 2012), pp. 899–907. ISSN: 1941-0107. DOI: 10.1109/TPEL.2012.2203151.

[9] Guipeng Chen, Yan Deng, and Luan Chen et al. “A Family of Zero-Voltage-Switching Magnetic Coupling Nonisolated Bidirectional DC-DC Converters”. In: *IEEE Transactions on Industrial Electronics* 64 (8 2017), pp. 6223–6233. ISSN: 1557-9948. DOI: 10.1109/TIE.2017.2682007.

[10] Yisheng Yuan and Xianglong Mei. “Five-level LLC resonant converter suitable for wide output voltage range”. In: *Electronic Letters* 54 (20 2018), 1187 – 1189. ISSN: 1350-911X. DOI: 10.1049/el.2018.6266.

Scientific Publications

International Journals

[j1] **Lilla Litvani** and Janos Hamar. “Control Features of a Four Channel Resonant Buck Converter”. In: *IET Power Electronics* 12 (8 2019). IF:2.839, Q1, 1931 – 1941. ISSN: 1755-4535. DOI: 10.1049/iet-pel.2018.6246.

[j2] **Lilla Litvani** and Janos Hamar. “Power Flow Control of Four Channel Resonant Step-down Converters”. In: *Journal of Power Electronics* 19 (6 2019). IF:0.901, Q2, 1393 – 1404. ISSN: 2093-4718. DOI: 10.6113/JPE.2019.19.6.1393.

[j3] **Lilla Litvani** and Janos Hamar. “Four Channel Buck Converter in Asymmetrical Continuous Current Conduction Mode”. In: *IEEE Canadian Journal of Electrical and Computer Engineering* (2019). IF:1.53, Q2, accepted for publication. ISSN: 2093-4718.

Hungarian Journals

[h1] **Lilla Litvani**. “Egy és kettős tekercselésű kalickás aszinkron generátorok összehasonlítása”. In: *Elektrotechnika* 15.12 (2015), pp. 15–18. ISSN: 0367-0708.

Conference Proceedings

[p1] **Lilla Litvani** and Janos Hamar. "New Five Level Resonant DC/DC Buck Converter". In: *Power Electronics and Motion Control Conference (PEMC), 2018 IEEE International*. 2018. DOI: 10.1109/EPEPEMC.2018.8521957.

[p2] **Lilla Litvani** and Janos Hamar. "Asymmetry Between Main Channels of a Multilevel Buck Converter - Operation in Steady State". In: *2nd International Conference on Smart Energy Systems and Technologies, IEEE SEST*. 2019. ISBN: 978-1-7281-1156-8. DOI: 10.1109/SEST.2019.8849026.

[p3] **Lilla Litvani** and Janos Hamar. "New Five Level Resonant DC/DC Buck-Boost Converter". In: *1st International Conference on Smart Energy Systems and Technologies, IEEE SEST*. 2018. ISBN: 978-1-5386-5327-2. DOI: 10.1109/SEST.2018.8495746.

[p4] **Lilla Litvani** and Janos Hamar. "Operation of New Five Level Resonant Buck-Boost Converter at Asymmetrical Outputs". In: *1st International Conference on Smart Energy Systems and Technologies, IEEE SEST*. 2018. ISBN: 978-1-5386-5327-2. DOI: 10.1109/OPTIM.2014.6851002.

[p5] **Lilla Litvani**, Peter Stumpf, and Janos Hamar. "Active and Reactive Power Distribution Among Multiple DFIG WTSs in an Isolated Microgrid". In: *ELECTRIMACS 2017*. 2017.

[p6] **Lilla Litvani**. "Smart Grid Control with Holons and Agents - State of the Art and Future". In: *Automation and Applied Computer Science Workshop*. 2015. ISBN: 978-963-313-187-9.

[p7] **Lilla Litvani**. "Power Optimisation of Induction Generators Used in Wind Power Plants". In: *Automation and Applied Computer Science Workshop*. 2016. ISBN: 978-963-313-187-9.

[p8] **Lilla Litvani**. "Improving the Total Efficiency of Multiple Parallel Connected Wind DFIGs". In: *Automation and Applied Computer Science Workshop*. 2017. ISBN: 978-963-313-187-9.

[p9] **Lilla Litvani** and Janos Hamar. "Multi-ágens és holonikus rendszerek a smart grid szabályozásban". In: *V. Mechwart András Ifjúsági Találkozó*. 2015.