INVESTIGATION ON THE EFFECTS OF DC-LINK CAPACITORS TO DC/AC CONVERTER UNDER VARIOUS OPERATION CONDITIONS

A Thesis

by

Mert Serdar Bilgin

Submitted to the
Graduate School of Sciences and Engineering
In Partial Fulfillment of the Requirements for
the Degree of

Master of Science

in the
Department of Electrical and Electronics Engineering

Özyeğin University
May 2019

INVESTIGATION ON THE EFFECTS OF DC-LINK CAPACITORS TO DC/AC CONVERTER UNDER VARIOUS OPERATION CONDITIONS

Approved by:

Dr. Göktürk Poyrazoğlu, Advisor
Department of Electrical and
Electronics Engineering
Özyeğin University

Assoc. Professor H. Fatih Uğurdağ
Department of Electrical and
Electronics Engineering
Özyeğin University

Assoc. Professor Mutlu Boztepe
Department of Electrical and
Electronics Engineering
Ege University

Dr. Ahmet Tekin
Department of Electrical and
Electronics Engineering
Özyeğin University

Dr. Özgür Tamer
Department of Electrical and
Electronics Engineering
Dokuz Eylül University

Date Approved: 29 May 2019

To My Parents,

Muradiye and Hamdi Bilgin

for their patience and support

in all aspects of my life

ABSTRACT

In the designing stage of a DC/AC converter, determining parameters of components has an essential role such as value, size and material type. DC-Link capacitors are the critical components for DC/AC converters and define the lifetime of the converter. A grid-connected converter must provide related standards and grid regulations done by operating country even though poor operating conditions. Effective power generation through a grid-tied DC/AC converter faces many challenges that cause less lifetime and inproper working of the device due to several factors including but not limited to unstable grid voltage, change of DC input voltage and different power factors. Grid voltage unbalance causes higher THD values on grid currents than normal grid conditions. THD value of grid current is limited by the IEEE 519-2014 standard. Unstable grid conditions show different results because of the value and type of DC-Link capacitors. In this thesis, after the introduction of topologies, basics of control methods, PWM methods of a DC/AC converter then two types of capacitors (electrolytic and film capacitors) are compared with different grid voltage conditions and power factor values for grid-tied 10 kVA DC/AC converter. On the other hand, the lifetime calculation theory of a electrolytic capacitor is interpreted and calculations are done for electrolytic capacitors in different operating conditions. Lastly, an unbalance voltage controller added to the system to observe effects on output current quality for an electrolytic DC-Link capacitor. All the work is done by simulation software PLECS, results are compared and explained.

ÖZETÇE

DC/AC çeviricilerin tasarım aşamasında, miktar, boyut ve materyal tipi gibi komponent parametrelerinin belirlenmesi önemli rol almaktadır. DC-Link kondansatörleri DC/AC çeviricilerinin ömrünü belirlediğinden dolayı kritik devre elemanlarıdır. Şebekeye bağlı bir çevirici ilgili ülkenin şebeke standartlarına ve düzenlemelerinden kötü çalışma koşullarında dahi uymak zorundadır. Şebekeye bağlı bir DC / AC dönüştürücüyle etkili enerji üretimi, kararsız şebeke voltajı, DC giriş voltajının değişmesi ve farklı güç faktörleri dahil ancak bunlarla sınırlı olmamak üzere çeşitli faktörler nedeniyle daha az kullanım ömrüne ve cihazın yanlış çalışmasına neden olan birçok zorlukla karşı karşıyadır. Dengesiz şebeke koşulları, dengeli şebekeye oranla şebeke akımlarında daha fazla toplam harmonik bozunumuna (THB) neden olmaktadır. Şebeke akımının THB değeri IEEE 519-2014 standardı ile sınırlandırılmıştır. DC-Link kondansatörlerinin tipi ve değeri farklı şebeke koşullarında sonuçların değişmesine neden olabilir. Bu tezde, DC/AC çeviricilerin devre yapıları, kontrol ve modülasyon tekniklerine giriş yapıldıktan sonra, şebekeye bağlı 10 kVA DC/AC çeviricide, farklı şebeke gerilimi, ve güç faktörü koşullarında elektrolitik ve film kondansatör tipleri karşılaştırılmıştır. Ayrıca elektrolitik kondansatörler için ömür hesabının matematiği anlatılmış ve hesaplamalar yapılmıştır. Son olarak, dengesiz gerilim kontrolcüsü tasarlanmış ve sisteme eklenerek çıkış akımı THB üzerine etkisi incelenmiştir. Tüm çalışmalar PLECS benzetim yazılımında yapılmıştır, sonuçlar karşılaştırılmış ve açıklanmıştır.

ACKNOWLEDGMENTS

I would like to express my sincerest thanks to Dr. Göktürk Poyrazoğlu for his guidance, support and valuable contributions throughout the preparation for this thesis.

I express my deepest gratitude to my family, my father Hamdi, my mother Muradiye, and my brother Burak for their encouragements and support throughout my education.

I would like to thank my colleagues Mert Aktem, Yılmaz Can, Ercan Er, Nemid Mahir Makineci and all my friends for their help and support.

I also would like to thank I am grateful to Özyeğin University Department of Electrical and Electronics Engineering faculty and staff for their help and encouragement throughout my graduate studies.

I am grateful to Vestel Electronic Corporation, Power Electronic Design Group Team for their help and support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The importance of renewable energy sources rises day by day with the increase in demand and environmental conditions. Therefore, the number of grid-tied power generation systems increases with the proportional to the demand such as solar and wind. Up to now, the energy generation plants have had great size and a centralized structure. However, the importance of distributed energy generation plants increases with the rise of renewable energy sources. There is a transition in power systems from being centralized to a system consist of many distributed generation systems [1], [2]. Especially, grid-tied DC/AC converters take large share from the distributed energy generation systems [3].

Voltage source converters have been used in industry for direct current (DC) to alternating current (AC) power conversion since the early 1960s [4]. Grid-tied DC/AC converters have become popular with the rise of renewable sources. DC/AC converters convert DC voltage that is generated by renewable sources such as wind and solar to AC electrical power. While grid-tied DC/AC converters inject the energy to the power system, DC/AC converters must be synchronized to the grid with the same frequency and phase. Furthermore, this synchronization requires to comply with some international standards. Therefore, there are boundaries to remain connected to the grid [5]. However, the grid is not always a balanced system [6]. For an AC power system, unbalanced operating voltages are quite common, especially for a weak power system. The reason of the unbalanced three phase voltages can be any of the followings: a renewable voltage source, an unevenly distributed single-phase load, a nonlinear load, a phase to phase load and so on [7]-[9]. It is expected to operate at various power factor from grid-tied DC/AC converters under unbalanced grid conditions. The operating power factor of the DC/AC converter could be lagging or leading [10]. Therefore, a grid-tied DC/AC converter must operate under unbalanced grid conditions, different power factors.

Generally, the input of the grid-tied DC/AC converter is renewable sources. The output DC voltage of the renewable sources oscillates during the operation of inverter because of the change of the irradiation, speed variation of the wind and so on. Thus, a grid-tied DC/AC converter must operate in different DC input voltages.

Figure 1.1 shows the block diagram of the grid-tied DC/AC converter system.

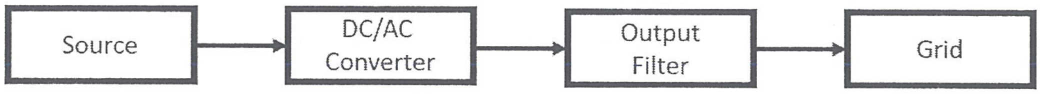

Figure 1.1: Block diagram of grid tied DC/AC converter system

Our contributions are to emphasize the importance of the DC-Link capacitance for system stability. Possible results and impacts of the replacing electrolytic capacitor to film capacitor with equal volume for a DC/AC converter design are observed. Furthermore, the importance of the DC-Link capacitor for the reliability for DC/AC converters. Possible results and effects of different grid conditions and power factor operations on DC/AC converter's lifetime are studied.

1.1 DC/AC Converter

DC/AC converters or inverters are mainly used to convert a constant DC voltage into AC voltage. There are many types of DC/AC converters are used in the industry. Grid-tied DC/AC converters can be separated into four groups which are, structural topologies, transformerless topologies, multilevel topologies, and grid connection topologies [11]. Figure 1.2 shows the classification of grid-tied DC/AC converter topologies.

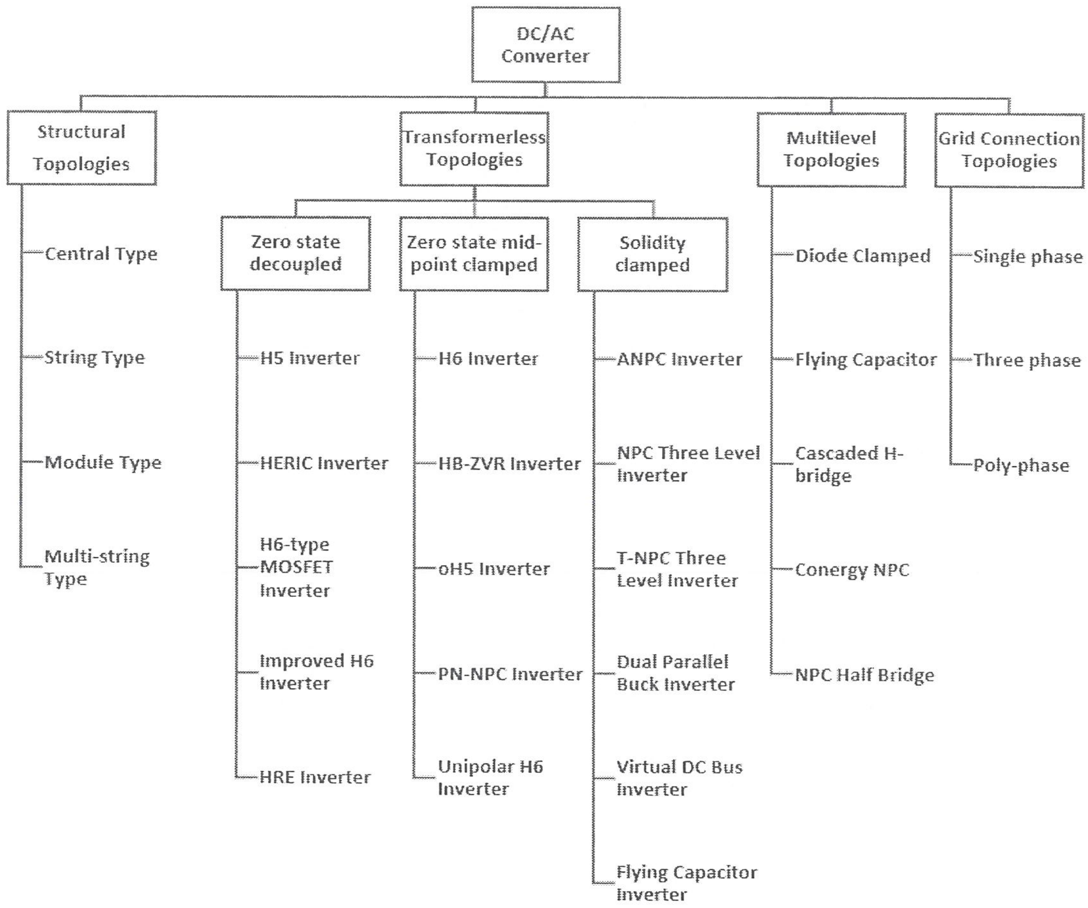

Figure 1.2: Classification of grid-tied DC/AC converter topologies

Structural topologies are categorized based on the input power rate and size of the DC/AC converters. Central Type DC/AC converter is used for medium voltage (MV) applications [11]. Central type DC/AC converters are fed by combining series and parallel solar panel strings or wind turbines. The efficiency of central type inverter is lower than other topologies. Therefore, central type DC/AC converters have disadvantages because of their high power loses and low power tracking capabilities. String and Multi-string type inverters are more useful because they have high power tracking capability and high efficiency. They are mostly used in solar farms. Module Type DC/AC converters are connected to only one solar panel and they have individual power tracking and high efficiency. However, module type inverters are a costly option [12].

Transformerless topologies are the second group of grid-tied DC/AC converters and divided into three subgroups as, zero-state decoupled, zero state mid-point clamped and solidity clamped. The classification of transformerless topologies is based on the leakage current characters and decoupling techniques [11]. There are many inverter topologies under the transformerless group, but most of these topologies are theoretical approaches. Neutral point clamped (NPC) three level inverter and T-type neutral point clamped (TNPC) three-level inverter have gained more and more importance in the market [13].

There is also a multilevel topologies group under grid-tied DC/AC converters. Multilevel inverters are mainly used in medium or high power system applications, such as static reactive power compensation and adjustable-speed drives. For high power application, multilevel DC/AC converters are the only option because of the high power semiconductor switching losses. In this type of application, switching frequency is too low to obtain high efficiency. Thus, the level of the DC/AC converters increases to get low total harmonic distortion (THD) on the output current [14].

Grid-tied inverters are also classified based on the grid connection types. The grid-tied DC/AC converters might be single phase, three-phase or poly-phase. Single phase grid-tied inverters are highly used in residual regions and low power application. Three-phase DC/AC converter type is most common grid-tied converter tied and mostly used in solar farms, wind farm, other renewable generation units. Three phase grid-tied converters can also be separated into two subgroups as three wire or four wire depending on the usage of the neutral line. Poly-phase topologies are used in special projects and they are not common in grid-tied DC/AC converters.

1.2 Grid Connection Requirements of DC/AC Converter

1.2.1 Reactive Power Support

Recently, the grid-tied DC/AC converters are widely used with the usage of the renewable source as a power source because of global warming and environmental conditions. The large scale grid-tied inverter systems have gained importance for the market and the renewable power plants have rapidly expanded from several to hundreds of megawatts [10]. Most of the renewable power plants are connected to low voltage distributed power systems. Each distribution system has its own system type or grid characterization because every country determines its own regulations and requirements [15].

Normally, distributed power plants are designed to inject active power to the grid because of to get maximum profit. However, power plants must provide reactive power to the grid because of some grid requirements. One of the requirements is reactive power support to the grid in case of the voltage unbalance, decrease or increase according to grid-code certification of German Association of Energy and Water Industries (BDEW) and VDE-AR-N 4105 [16]. If the grid voltage changes more than 10%, the grid-tied DC/AC converter must support the grid with the rejection or injection reactive power [10]. Therefore, grid-tied inverters can operate under different power factors. Figure 1.3 shows the reactive current support if the grid voltage fault exceeds 10% of rated voltage according to the German grid code.

1.2.2 Grid Tied DC/AC Converter Output Current Total Harmonic Distortion (THD) Limitations

The usage of the grid-tied inverters change the sinusoidal nature of the AC power current. Power electronic converters create harmonic currents in power systems. The result of these harmonic currents in the power system can cause interfaces with communication equipment and other types of circuits. These harmonic currents also lead

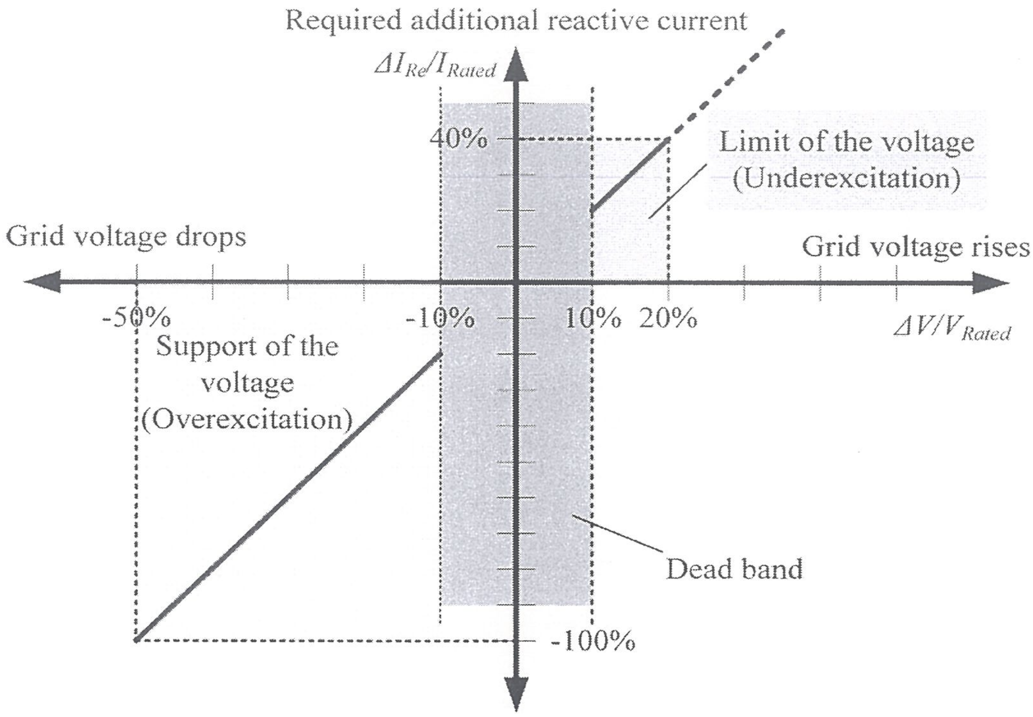

Figure 1.3: Voltage support when grid fault exceeds 10% of rated voltage [10]

the increase loses in the transmission system and grid-connected systems. Furthermore, harmonic currents in the AC power system might cause heating in electronic devices such as motors and transformers [17].

There are several standards that include the current THD limitation for a better power system. Managing harmonics in a power system is considered a joint responsibility involving both end-users and system owners or operators. Harmonic limits are recommended for both voltages and currents [17]. According to IEEE 519-2014, output current THD of a grid-connected DC/AC converter must be below the limitations. Limitations are variable and depend on the ratio of short-circuit current (I_{sc}) and converter rated current (I_L). The IEEE 519-2014 current THD limitations at point of common coupling (PCC) are given in Table 1.1 [17].

Table 1.1: Current Distortion Limits for Systems Rated 120V through 69 kV

Maximum harmonic current distortion in percent of I_L						
I_{SC} / I_L	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h \leq 50$	THD
<20	4.0%	2.0%	1.5%	0.6%	0.3%	5.0%
20<50	7.0%	3.5%	2.5%	1.0%	0.5%	8.0%
50<100	10.0%	4.5%	4.0%	1.5%	0.7%	12.0%
100<1000	12.0%	5.5%	5.0%	2.0%	1.0%	15.0%
>1000	15.0%	7.0%	6.0%	2.5%	1.4%	20.0%

1.3 *Lifetime Expectations of Grid-Tied DC/AC Converter*

The lifetime of the grid-tied DC/AC converter gains importance with the growing number of the installed and connected plant [18]-[20]. Installation site affects the lifetime of the grid-tied DC/AC converter. The ambient temperature, cosmic ray radiation and humidity are the most common effects on lifetime [21], [22]. In 2015, the lifetime of the commercial, residual and utility sizes grid-tied inverters were 15 years but it will increase up to 30 years [23]. The cost of grid-tied DC/AC converters in a distributed power system like solar and wind farm goes up to 59% if any failure occurs [24]. Therefore, lifetime prediction is crucial for a grid-tied DC/AC converters [21].

Foible of a grid-tied inverter is electrical components. A grid-tied inverter occurs more than a thousand electrical component. The weakest components in the DC/AC converters are DC-Link capacitors if any failure condition does not happen. Because of the switching operation of the inverter, high-frequency ripple currents flow on the DC-Link capacitors. Because of the ESR, the heat generated inside the DC-Link capacitors. Therefore, the ratio of the ripple currents that flow on DC-Link capacitors is an important parameter for lifetime expectation. Furthermore, ripple current may be affected by the operation condition of the DC/AC converter as DC-Link voltage and power factor.

1.4 Scope of Thesis

The main scope of the thesis is to investigate the effects of the different operation condition of grid-tied DC/AC converter on the output current harmonics and DC-Link capacitor lifetime. Furthermore, two capacitor types are compared based on the output current THD. A complete simulation model is created for observation of the effects in simulation software which is PLECS. This study includes theoretical analysis of a grid-tied DC/AC under various operating conditions.

Chapter 1 is the motivation of the study. The general information about grid-tied DC/AC converter is given. The limitations of the grid connection of an inverter are explained. Furthermore, the required operating conditions to support the grid based on the standards and grid codes are given. The last topic in this chapter is the lifetime expectation of the grid-tied DC/AC converters.

Chapter 2 involves the theory. The necessary information to understand the background of this study is explained. Definition of grid voltage terms and power are given. This chapter also has a brief description of the DC-Link capacitor types. Furthermore, common control strategies and DC/AC converter topologies are explained. There are also formulations of lifetime calculation for DC-Link capacitors

Next chapters show the system implementation and results. All results are given and described. DC/AC converter output ripple currents, output current THDs and DC-Link capacitor lifetime calculations are the results of this study. Furthermore, the effect of the balance algorithm is investigated in this chapter.

The main focus of this thesis is analyzing operation conditions and also grid conditions on a grid-tied DC/AC converters. Possible conditions are created and effects on a 10 kVA grid-tied DC/AC converter are observed.

CHAPTER II

THEORY

2.1 Definition of Power

The definition of the power is based on the knowledge and agreement which have been developed since the 1940s [25]. This part of the thesis provides the definition of the electrical power to quantify the electrical energy in three phase system under sinusoidal balanced condition based on [25]. In this case, assuming a counterclockwise rotating positive-sequence system, a, b, c, the line-to-neutral voltages are as follows:

$$V_a = \sqrt{2}V \sin(\omega t) \tag{1}$$

$$V_b = \sqrt{2}V \sin(\omega t - 120°) \tag{2}$$

$$V_c = \sqrt{2}V \sin(\omega t + 120°) \tag{3}$$

Line currents have also similar equations and they are as follows;

$$I_a = \sqrt{2}I \sin(\omega t - \theta) \tag{4}$$

$$I_b = \sqrt{2}I \sin(\omega t - \theta - 120°) \tag{5}$$

$$I_c = \sqrt{2}I \sin(\omega t - \theta + 120°) \tag{6}$$

where

V is the root-mean-square (rms) value of the line-to neutral voltage (V)

I is the rms value of the current (A)

ω is the angular frequency $2\pi f$ (rad/s)

f is the power system frequency (Hz)

θ is the phase angle between the current and the voltage (rad)

t is the time (s)

2.1.1 Instantaneous power (W)

For a sinusoidal and balanced three-phase system, the summation of the phase current is zero, $I_a + I_b + I_c = 0$. The instantaneous power, p, for a balanced three-phase system is calculated as follows [25]:

$$p = V_a I_a + V_b I_b + V_c I_c = P \tag{7}$$

The instantaneous power, p, is constant and equal to active power, P, in three-phase systems, if line voltages and currents are balanced. The instantaneous active power p_a is the rate of flow of the energy, w_a [25].

$$w_a = \int_{t_0}^{t} p_a dt \tag{8}$$

2.1.2 Active Power (W)

The active power P, which is also called real power, is the actually consumed or generated power in the power system. Active power is equal to the instantaneous power in balanced three-phase systems. The active power can be also calculated with the average value of the instantaneous power during the measurement time interval τ to $\tau + kT$ [25].

$$P = \frac{1}{kT} \int_{\tau}^{\tau+kT} p dt \tag{9}$$

$$P = 3VI \cos\theta = \sqrt{3} V_{ll} I \cos\theta \tag{10}$$

where

V_{ll} is line-to-line rms voltage

$T = \frac{1}{f}$ is the cycle time (s)

k is the positive integer number

τ is the moment where the measurement starts

2.1.3 Reactive Power (VAR)

Reactive power Q is known as borrowed energy. Thus, reactive power is an imaginary power and could be inductive or capacitive depending on the type of the load or source. Reactive power flows forward and backward in a power system. The magnitude of the reactive power is equal to amplitude of the oscillating instantaneous reactive power [25].

$$Q = 3VI\sin\theta = \sqrt{3}V_{ll}I\sin\theta \tag{11}$$

2.1.4 Apparent Power (VA)

Apparent power S is the product of rms line-to-neutral voltage and rms line current. Apparent power covers the real and reactive power consumption or generation [25]. Figure 2.1 shows the relation between apparent power, real power and reactive power.

$$S = P + jQ = 3VI = \sqrt{3}V_{ll}I \tag{12}$$

$$|S| = \sqrt{P^2 + Q^2} \tag{13}$$

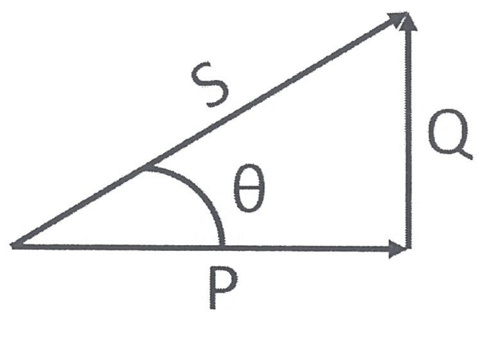

Figure 2.1: Power Triangle

2.1.5 Power Factor

Power factor pf is the ratio of the active power to the apparent power.

$$pf = \frac{P}{S} = \frac{3VI\cos\theta}{3VI} = \cos\theta \tag{14}$$

2.2 *Symmetrical Components of Power System*

Symmetrical components were discovered in 1918 by Charles Legeyt Fortescue and he presented it in [26]. A balanced grid has only positive sequence terms. However, in case of any unbalance grid condition, the grid has positive negative and zero sequence terms. The technique that was discovered by C.L. Fortescue allows decomposing any unbalanced system into a series of the balance system.

Unbalanced voltage condition in the grid system can be a result of many factors [7-9], these are:

- Lack of symmetry in transmission line impedance
- Unevenly distributed single-phase loads
- Open delta or wye transformers
- Nonlinear or phase to phase loads
- Faulty power factor compensation capacitor banks

Furthermore, voltage unbalance ratio can be calculated as follows:

$$\text{Voltage unbalance \%} = \frac{\text{Maximum deviation from average voltage}}{\text{Average voltage}} \text{ x } 100 \tag{15}$$

2.2.1 Symmetrical Components

A system of three unbalanced phasors can be separated into the three symmetrical components as follows [26]:

- Positive Sequence: A balanced three-phase system with the same phase sequence as the original sequence.
- Negative sequence: A balanced three-phase system with the opposite phase sequence as the original sequence.
- Zero Sequence: Three phasors that are equal in magnitude and phase.

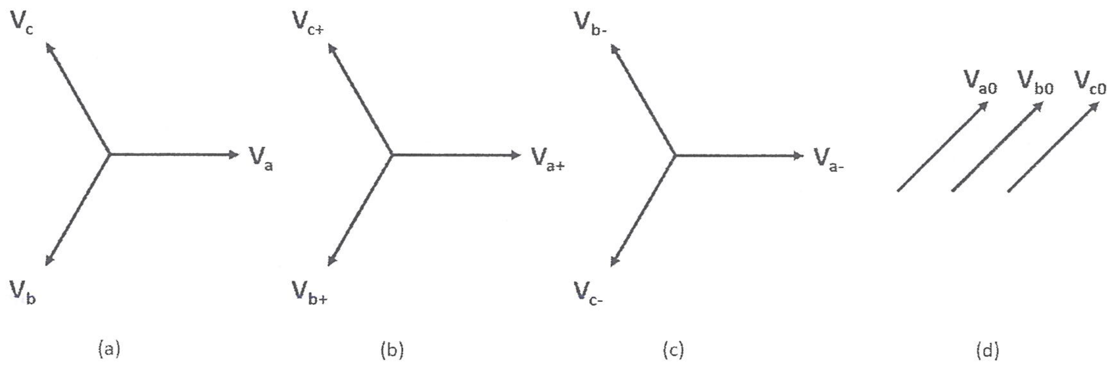

Figure 2.2: Representation of (a) an unbalanced network, its (b) positive sequence, (c) negative sequence and (d) zero sequence

2.2.2 Symmetrical Component Transformation

The symmetrical components can be used to determine any unbalanced current or voltage. Definition of a-operator that is going to used in the symmetrical components transformation.

$$a = e^{j120^\circ} = -\frac{1}{2} + j\frac{\sqrt{3}}{2} \tag{16}$$

$$a^2 = e^{j240^\circ} = -\frac{1}{2} - j\frac{\sqrt{3}}{2} = a^* \tag{17}$$

Also note that

$$1 + a + a^2 = 0 \tag{18}$$

Now, V_{b+}, V_{b-}, V_{c+} and V_{c-} can be rewritten with using the of the a-operator and V_{a+} and V_{a-} from Figure 2.2.

$$V_{b+} = a^2V_{a+} \text{ and } V_{c+} = aV_{a+} \tag{19}$$

$$V_{b-} = aV_{a-} \text{ and } V_{c-} = a^2V_{a+} \tag{20}$$

The relation between V_{a0}, V_{b0} and V_{c0} can be extracted from Figure 2.2 (d) as follow:

$$V_{a0} = V_{b0} = V_{c0} \tag{21}$$

The symmetrical component transformation matrix is defined in (22). The symmetrical component transformation matrix combines the symmetrical components and unbalanced network with the rearrangement of (19 - 21).

$$\begin{bmatrix} V_{a0} \\ V_{a+} \\ V_{a-} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{22}$$

(22) can be rewritten as (23)

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_{a0} \\ V_{a+} \\ V_{a-} \end{bmatrix} \tag{23}$$

From (23), three-phase voltages can be rewritten in symmetrical components of phase a:

$$V_a = V_{a0} + V_{a+} + V_{a-} \tag{24}$$

$$V_b = V_{a0} + a^2V_{a+} + aV_{a-} \tag{25}$$

$$V_c = V_{a0} + aV_{a+} + a^2V_{a-} \tag{26}$$

2.3 DC-Link Capacitor Types in DC/AC Converter

In the design procedure of a DC/AC converter, mostly, there are two options for a DC-Link capacitor; film capacitor and aluminum electrolytic capacitor. The major considerations on the selection of a DC-Link capacitor are its lifetime and the ripple current capability. Electrolytic capacitors have been used in DC/AC converters for many years and they have higher capacitance per volume ratio compared has lower ESR than the electrolytic capacitor. Thus, a film capacitor produces less heat than an electrolytic capacitor and it has a longer lifetime [27, 28]. Electrolytic capacitors are being used in most of the projects because of design considerations but a film capacitor may be a good choice for a DC-Link [28, 29]. Figure 2.3 shows the lumped model of capacitors [30]. R_p is the insulation resistance. R_d is the dielectric loss due to dielectric absorption and molecular polarization and C_d is the inherent dielectric absorption [30]. The widely used simplified capacitor model is composed of C, R_s, and L_s. C is the capacitance, R_s is the equivalent series resistance (ESR) and L_s is equivalent series inductance (ESL) [30].

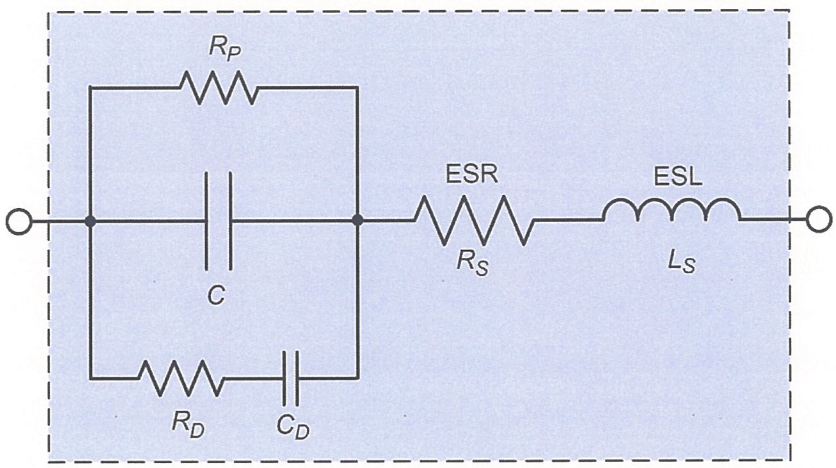

Figure 2.3: Simplified lumped model of capacitors

2.3.1 Aluminum Electrolytic Capacitors

Aluminum electrolytic capacitors can achieve high capacitance value because of the structure. Electrolytic capacitors are polarized with a positive and negative terminal. Electrolytic capacitors have a winding structure and are filled with chemical or solid polymer electrolyte [31]. Figure 2.4 shows the winding construction of electrolytic capacitors [31]. However, the electrolytic capacitor has high ESR because of winding structure. Furthermore, electrolytic capacitor's leakage current is high, insulation resistance is low, and the tolerances are broad. Therefore, the limited lifetime of an electrolytic capacitor is the major drawbacks.

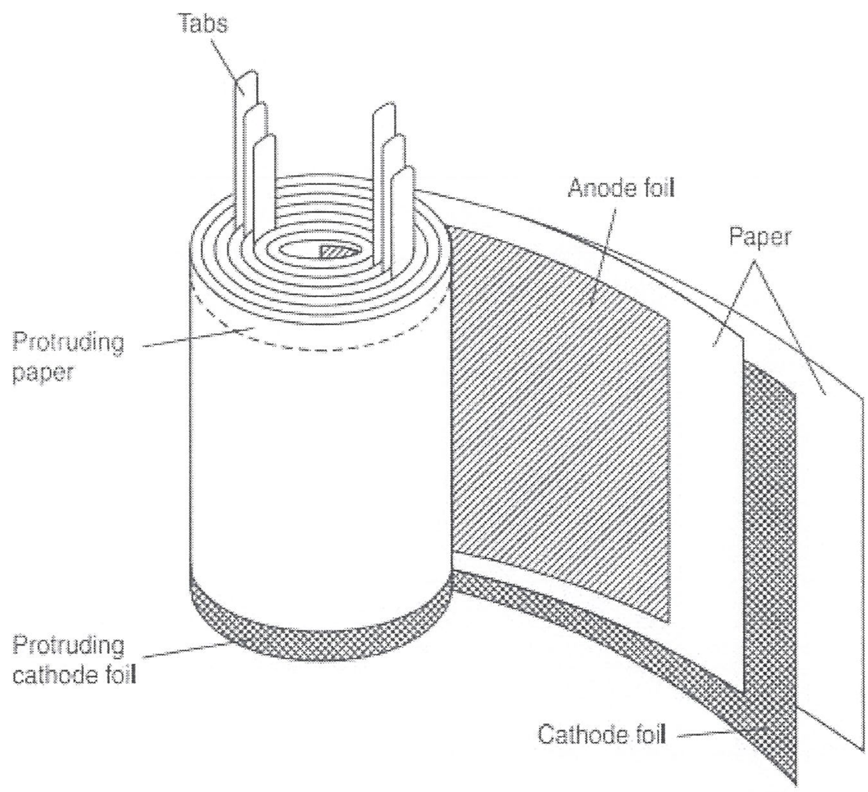

Figure 2.4: Winding construction of an aluminum electrolytic capacitor

2.3.2 Film Capacitors

There are many types of film capacitor exist in the market. The main cause of this variation is the insulation material inside the film capacitors. Dielectric material affects strongly the characteristic and application possibilities of film capacitors. Therefore, film capacitors are separated into different groups according to the type of dielectric materials [32]. Figure 2.5 shows the classification of film capacitors [32].

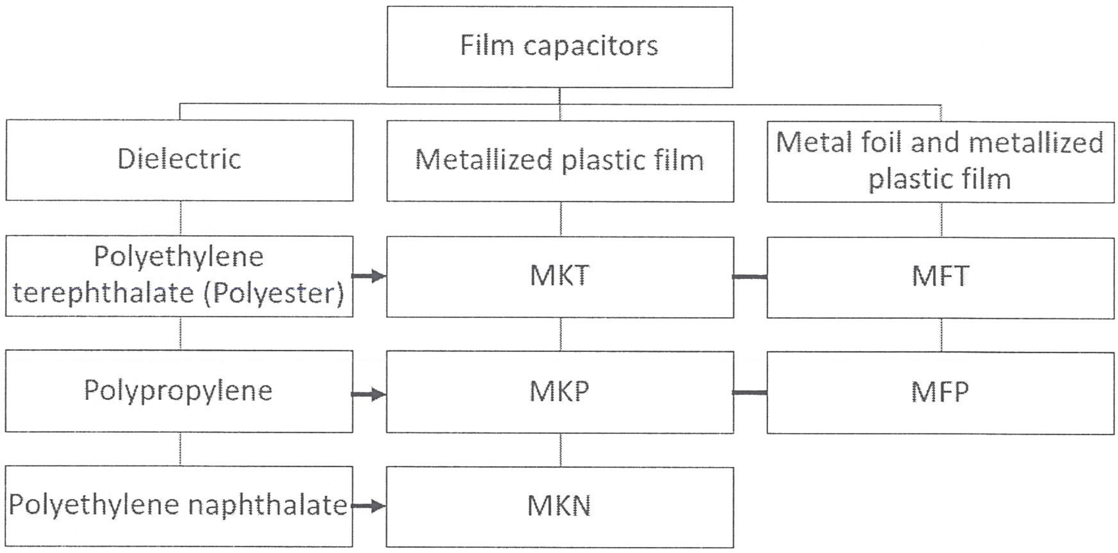

Figure 2.5: Classification of film capacitors

Furthermore, Figure 2.6 shows the internal structure of foil and film capacitor for better understanding [32].

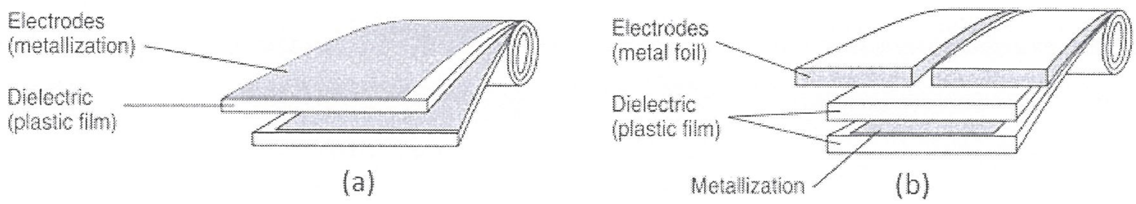

Figure 2.6: Internal structure of (a) film arrangements, (b) foil arrangements

Film capacitor has great reliability and low ESR because of its internal structure.

Electrodes in film and foil capacitors are separated with sheets of metal foil wound with sheets of dielectric material as shown in Figure 2.6 [32]. However, the capacitance of the film capacitor per volume is lower than aluminum electrolytic capacitor. Film capacitors cover more space than the electrolytic capacitor for equal capacitance. Thus, the size of the grid-tied DC/AC converter is important and oversize products is not an accepted value in the market. The weakness of the film capacitors is their low capacitances per volume.

2.4 DC-Link Capacitor Lifetime Calculation

In section 1.3, the importance of the grid-tied DC/AC converter lifetime is discussed. In a grid-tied inverter, DC-Link capacitors are thought as the weakest part for the reliability because of the operating conditions such as power cycling, high internal capacitor temperature [33]. Moreover, in many applications, the lifetime of the electrolytic capacitor determines the lifetime of the devices [34]. Because of the structure of the electrolytic capacitor that is discussed in section 2.3, it has high ESR. Thus, the electrolytic capacitor produces heat during operation. The electrolytic capacitor has fluid due to its structure. The ratio of the fluid decreases day by day during the operation of the DC/AC converter because of the rise in the internal temperature of the capacitor which results of the produced heat [27, 28, 35]. The change of the liquid ratio could be caused instability operation of the DC/AC converter because the capacitance is changed in time [35].

Current ripple on the DC-Link capacitors is related to the internal temperature rise. The increase of the current ripple produces higher heat in the capacitor. Therefore, the quantity of the DC-Link current ripple affects the lifetime of the grid-tied DC/AC converter because electrolytic capacitor fluid change speed is determined by the produced heat during operation and heat is related with the current ripple.

Furthermore, the DC-Link capacitor lifetime calculations are generally applied to the electrolytic capacitor. The lifetime of film capacitors is quite higher than the electrolytic capacitor because of the internal structure. Film capacitors have low ESR and great ripple current capability.

2.4.1 Ripple Current Model for DC-Link Capacitors

The ripple current causes a self-heating of the electrolytic capacitor. Ripple current depends on ESR at a specific frequency [36]. Thus, the rated ripple current model is necessary because ripple currents at any frequencies contribute to self-heating of the electrolytic capacitor [37].

A correction factor K_{f_n} must be introduced to obtain rated ripple current because the correction factors for various frequencies are the result of the frequency dependency of the ESR [36, 37]. (27) defines the correction factor [36]. The required information to calculate the correction factor is given by the manufacturer in the product datasheet.

$$K_{f_n} = \sqrt{\frac{ESR_{100Hz}}{ESR_{f_n}}} \tag{27}$$

Rated current ripple is derived from the DC-Link capacitor current. However, if the current ripple includes different frequency terms, the calculation becomes more difficult. Thus, it is necessary to know the rms of the capacitor ripple current at each frequency term, I_{f_n}. If DC-Link capacitor ripple current has different frequencies, rated current ripple, I_r can be calculated as (28) [37].

$$I_r = \sqrt{\left(\frac{I_{f1}}{K_{f_1}}\right)^2 + \left(\frac{I_{f2}}{K_{f_2}}\right)^2 + ... + \left(\frac{I_{fn}}{K_{f_n}}\right)^2} \tag{28}$$

where

I_r	is rms value of the rated ripple currents
$I_{f_1}...I_{f_n}$	are the rms value of ripple currents at frequencies $f_1...f_n$
$K_{f_1}...K_{f_n}$	are the correction factor for the current at frequencies $f_1...f_n$

2.4.2 Lifetime Model for DC-Link Capacitor

Lifetime models are important for lifetime estimation of the capacitors [30]. Manufacturers provide the lifetime of the capacitors in the datasheets, but these lifetime expectations are specified under maximum stress conditions such as maximum operating voltage and temperature. Therefore, the lifetime of the capacitor could be different in the application [38]. The lifetime model, L is given in [37] as follows:

$$L = L_0 \times K_R \times K_T \times K_V \tag{29}$$

where

L	is the lifetime model
L_0	is the lifetime of the capacitor which is given in the datasheet
K_R	is the ripple current factor
K_T	is the temperature factor
K_V	is the voltage factor.

The formulations of the K_R, K_T and K_V is given in (30), (31) and (32) respectively.

$$K_R = K_i^{A \times \frac{\Delta T_0}{10K}} \tag{30}$$

$$K_T = 2^{\frac{T_0 - T_a}{10}} \tag{31}$$

$$K_V = \left(\frac{U_a}{U_r}\right)^{-n} \tag{32}$$

$$A = 1 - \left(\frac{I_r}{I_0}\right)^2 \tag{33}$$

where

K_i	is the safety factor in the range of 2 to 4 [38]
I_0	is the maximum ripple limit of the capacitor at upper-temperature limit
Δ_{T_0}	is the internal temperature rise $\begin{cases} \Delta_{T_0} = 5K & \text{if } T_0 = 105°C \\ \Delta_{T_0} = 10K & \text{if } T_0 = 85°C \end{cases}$
T_0	is the upper category temperature of the capacitor

T_a	is the ambient temperature
U_r	is the rated voltage of the capacitor
U_a	is the operating voltage of the capacitor
n	is an exponent $\begin{cases} n = 2.5 & \text{if } 0.5 \leq \frac{U_a}{U_r} < 0.8 \\ n = 5 & \text{if } \frac{U_a}{U_r} \geq 0.8 \end{cases}$

Lifetime model is useful to see the effects of the operating conditions on the lifetime and the change of the operating condition is a design consideration because operating conditions can affect the lifetime [38].

2.5 DC/AC Converter Topologies

Grid-tied DC/AC converters are mostly voltage source topologies. These topologies have higher energy conversion efficiency and lower cost as compared to the current source topologies [39]. Classification of the grid-tied inverters is given in Figure 1.2. Transformerless grid-tied inverters are available in power ratings from several kVA to tens of kVA. Furthermore, transformerless grid-tied DC/AC converters are generally connected to low voltage distribution systems directly [39].

This section presents the three most common three-phase grid-tied DC/AC converter topologies in industry. First one is two-level grid-tied DC/AC converter. Then two three-level inverter topology are discussed. These topologies are three-level neutral point clamped (NPC) DC/AC converter and three-level T-type neutral point clamped (TNPC) DC/AC converter.

2.5.1 Two-level grid-tied DC/AC converter

The basic two-level, grid-tied three-phase inverter, presented in Figure 2.7. This three-phase DC/AC converter type has the minimum semiconductor switch count and the lowest conduction loses. The inverter is composed of six semiconductor switches. Only two switches in each phase are used to construct one inverter leg. Two switches in each phase are used to construct one leg. The AC output voltage from the inverter is obtained by controlling the semiconductor switches ON and OFF to generate the desired output. Different types of pulse width modulation (PWM) techniques are widely used to perform this task. This conventional two-level topology is the most established and widely used technique in the industry. However, this topology is losing its reputation with the improvement in technology and its high switching loses, output current/voltage ripple and low energy conversion efficiency [39].

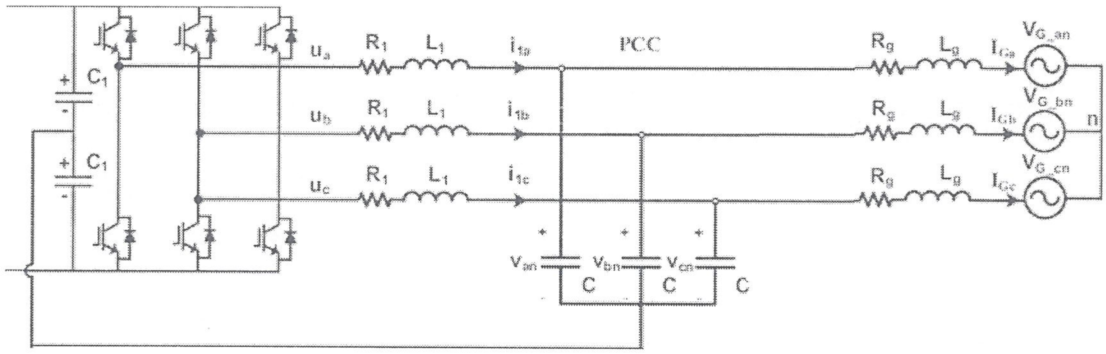

Figure 2.7: Grid-tied 2L DC/AC converter topology

2.5.2 Three-level grid-tied neutral point clamped (NPC) DC/AC converter

The basic function of the three-level DC/AC converter is similar to the two-level inverter. While the two-level inverter switches the output phases between the positive DC-Link voltage and the negative DC-Link voltage, the three-level inverter switches the output phases between the positive DC-Link voltage, the negative DC-Link voltage and the neutral point of the DC-Link capacitors. Therefore, this topology is called as three-level inverter because of the output voltage level count.

Three-level NPC DC/AC converter has reduced switching loses as compared to two-level inverter. The blocking voltage voltages of semiconductor switches are lower because the voltage rates are lower. This feature provides low power loses during the switching operation. However, the conduction loses rise because this topology has 12 semiconductor switches. However, increase in conduction loses is compensated by switching loss reduction. Thus, the overall energy conversion efficiency of NPC inverters is enhanced [39].

Furthermore, one other benefits of three-level NPC DC/AC converter is lower output harmonics and THD. Thus, the filtering effort is reduced. It provides lower filtering inductor at the output of the converter. Therefore, the power loses on output filter decreases. The total usage of the copper in filter inductor also decreases and the cost of the filter could be enhanced [40]. Figure 2.8 shows three-level grid-tied NPC DC/AC converter topology.

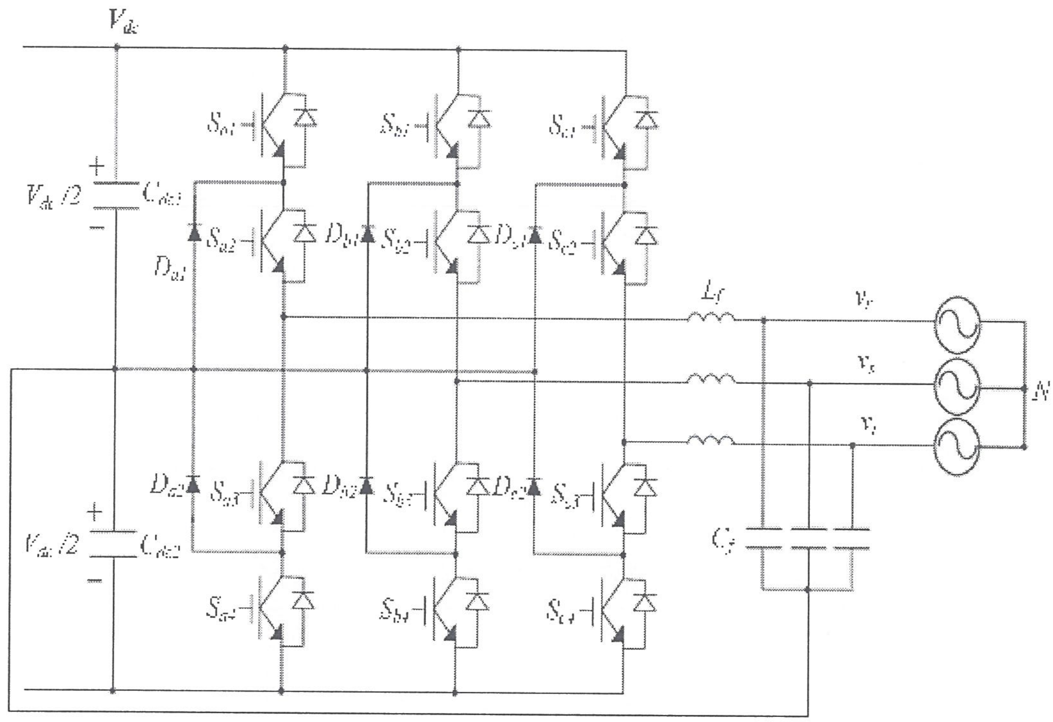

Figure 2.8: Grid-tied 3L NPC DC/AC converter topology

2.5.3 Three-level grid-tied t-type neutral point clamped (TNPC) DC/AC converter

T-type neutral point clamped inverters have same operational characteristics as the NPC inverter. This topology has 12 semiconductor switches as NPC DC/AC converter, but each inverter leg only has 2 semiconductor switches. The main difference between these two types of the three-level inverter is in further reduction of conduction losses by combining different types of devices as the clamping and main devices. Thus the conduction losses are reduced as compared to the NPC inverter [39]. However, the blocking voltages of the switching semiconductors are higher than NPC inverters. On the other hand, the energy conversion efficiency of TNPC inverter is as better as NPC inverters. Figure 2.9 shows three-level grid-tied TNPC DC/AC converter topology.

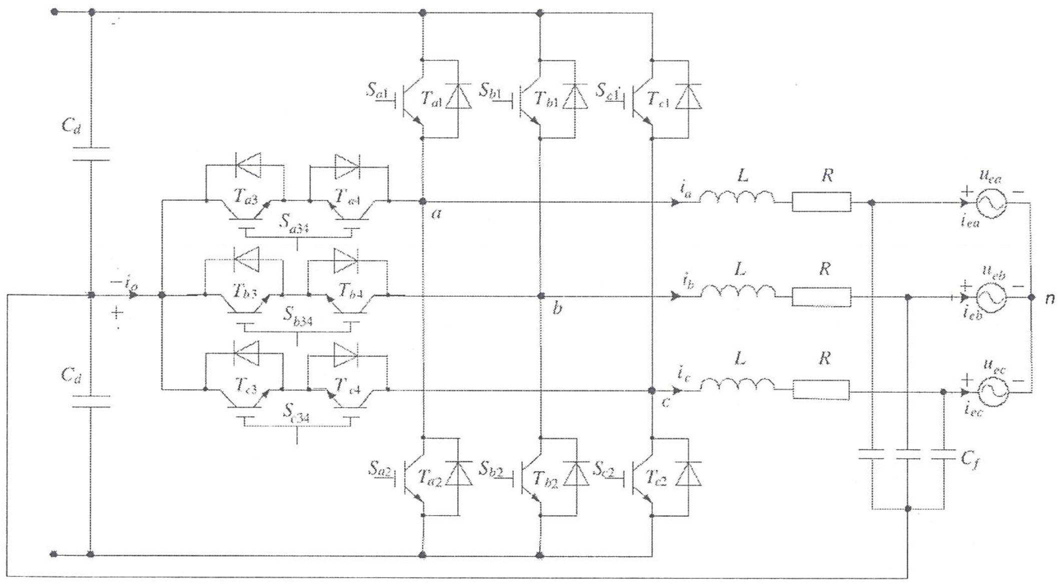

Figure 2.9: Grid-tied 3L TNPC DC/AC converter topology

2.6 Modulation Techniques of Grid-Tied DC/AC Converters

Three-phase two and three-level voltage source DC/AC converters are widely used in different branches of industry [41]. There are many PWM modulation techniques for two-level and three-level inverters. Figure 2.10 shows the classification of the modulation techniques that are used in DC/AC converters [42].

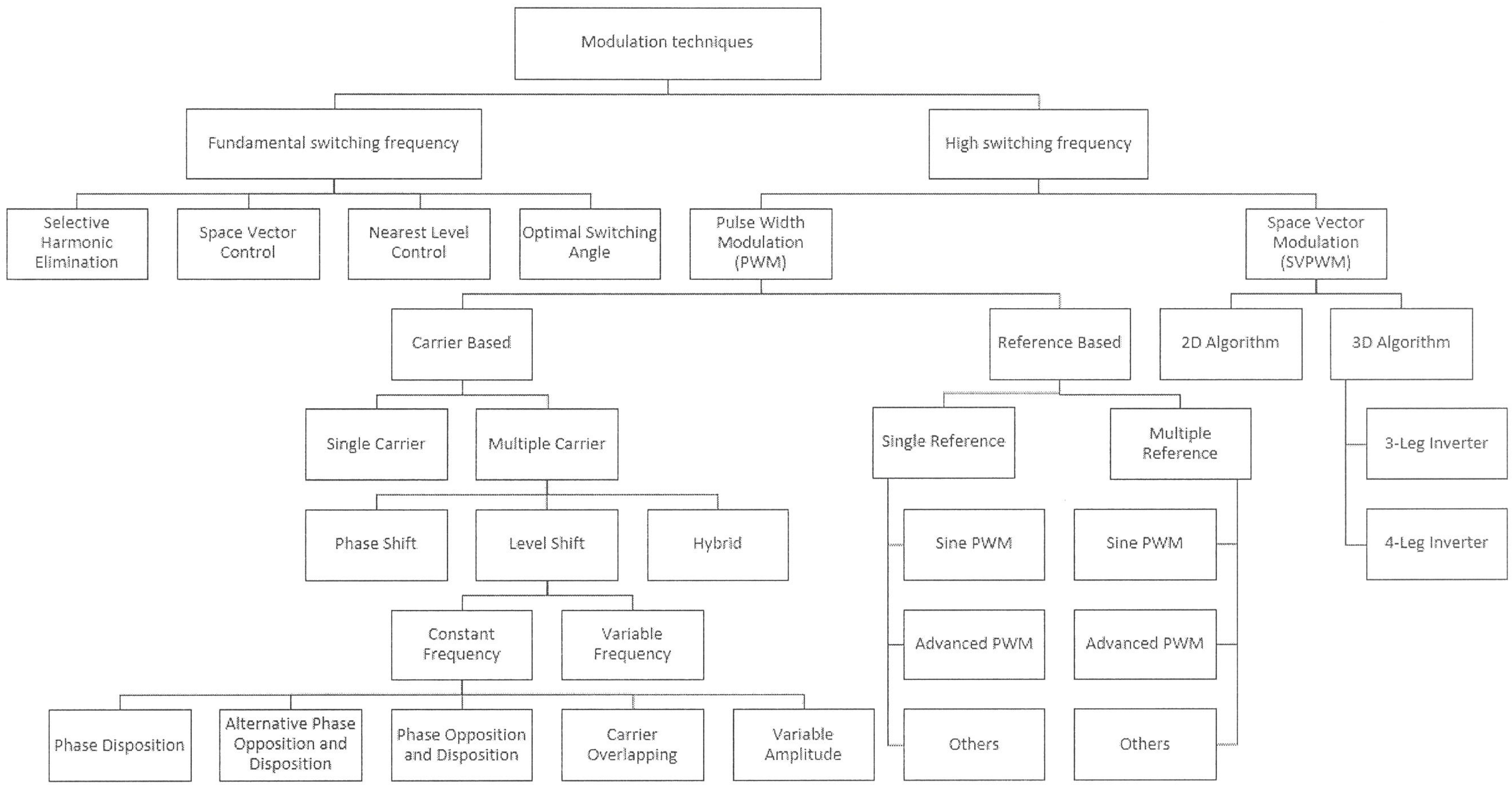

Figure 2.10: Classification of modulation techniques of DC/AC converters

The several popular modulation techniques are discussed and compared for two-level and three-level DC/AC converters in [43] and [44]. [43] presents the effects of the modulation type on DC-Link capacitor current and voltage ripple for two-level and three-level DC/AC converters. Each modulation technique has individual effects on DC-Link capacitor current and voltage ripple. One of the outputs of [43] is the temperature rise of the DC-Link capacitors. The increase of DC-Link capacitor temperature changes from 1.7 °C to 16.6 °C depending on the modulation technique.

In [44], the output voltage ripple of two-level and three-level DC/AC converters are discussed. There are also semiconductor loss comparisons for different modulation techniques. In almost all two-level modulation techniques, the semiconductor losses are higher than the three-level modulation technique [44]. The reason of this difference comes from the features of the topologies. It is discussed in section 2.5.

Furthermore, according to [44], each modulation technique causes different weighted THD and ripple on output voltages. Therefore, the modulation technique has great importance on the DC/AC converters internal operation dynamics like temperature rises, system energy conversion efficiency and output waveform quality.

2.7 Closed-Loop System Control Techniques

A suitable closed-loop must be designed for a grid-tied DC/AC converter because connecting to the distributed generation system plays a key role. The grid uncertainty, grid disturbance and a number of problems may occur if any negligence is shown in implementing closed-loop control structure [45]. There have been many types of control systems like single-loop and multi-loop discussed in the literature for developing power control, voltage and current control. Figure 2.11 presents the categorization of the classical closed-loop control technique [45]. Generally, in the closed-loop control structure of grid-tied DC/AC converter, the inner loop is for current regulation and the outer loop is for voltage control. There is also a power control loop located in the middle between the current control loop and voltage control loop [46-48].

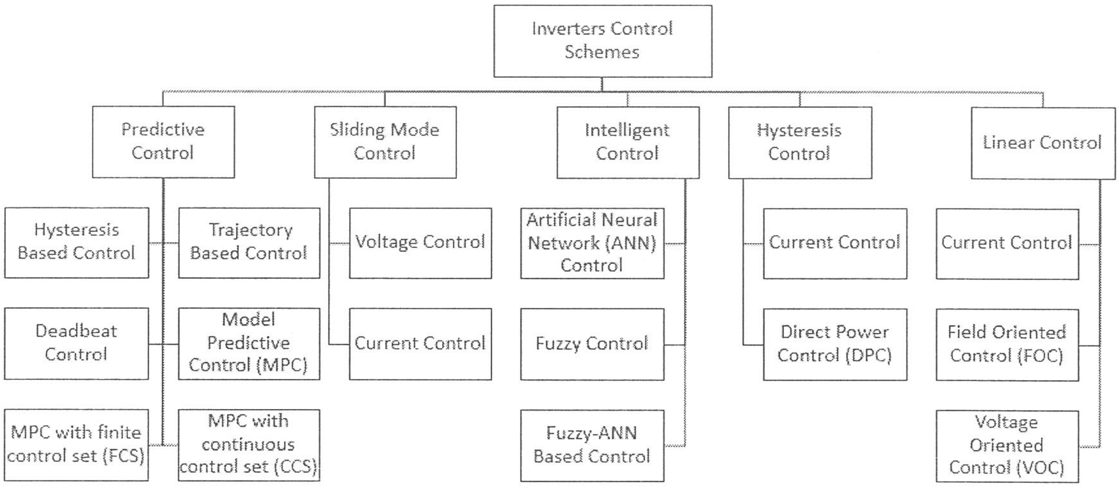

Figure 2.11: Classification of closed-loop control techniques for the voltage source DC/AC converters

2.7.1 Classical Control Techniques

The classical controllers include the category of controllers for subtracting or adding a proportion and to adjust the system stability [45]. These controllers involve proportional (P), proportional integration (PI) proportional integration derivative (PID) and proportional derivative (PD) controllers. These controllers are the most fundamental controllers in the industry to control linear systems. These controllers are also considered as the base of control theory. Most of the work in industry is designed with these controllers [49-52]. The fundamental benefits of classical control technique implementation are their ability to tune themselves according to the requirement of the plant and their simple structure [45]. They are the most commonly used controllers in the industry. Especially, PI controllers are generally used as current, voltage and also power controllers in the grid-tied DC/AC converters in the market. The structure of a PI controller is given in Figure 2.12.

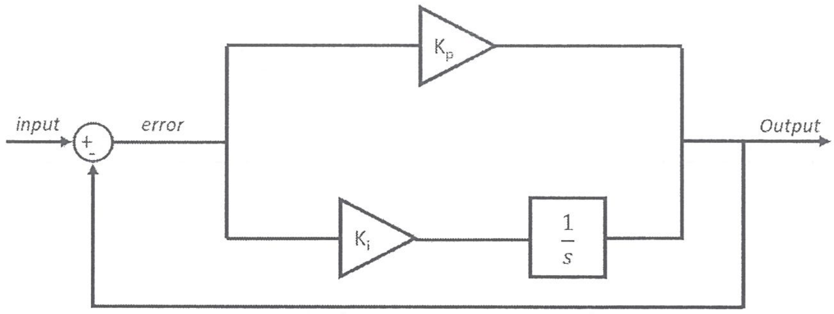

Figure 2.12: General structure of PI controller

If PI controller can be modelled as a transfer function that is the ratio of the output to the input. The transfer function of PI controller is given in (34).

$$G_{PI} = \frac{output}{input} = K_p + \frac{K_i}{s} \tag{34}$$

2.7.2 Phase Look Loop (PLL)

The phase angle of the grid is an important parameter for grid-tied DC/AC converters because, for a successful connection to the grid, the phase angle of the grid and the output voltage of DC/AC converter must be equal [53]. Furthermore, phase angle information may be used to calculate and control the flow of active/reactive power, synchronize the turning on/off of power devices or transform the feedback variables to a reference frame suitable for control purposes. The angle information is typically extracted using some form of a phase-locked loop (PLL) [54].

In the basic configuration of the PLL system, the phase voltages V_a, V_b and V_c are obtained from sampled line to neutral voltages. Then, the stationary reference frame sampled voltages are transformed to the synchronized reference frame voltages V_d and V_q using Clarke-Park conversion. V_d and V_q are synchronized to the grid frequency. The angle Θ used in the Clarke-Park conversion is obtained by integrating a frequency command ω^*. If the frequency command ω^*. Is identical to the grid frequency, the voltages V_d and V_q appear as DC values depending on the angle Θ. Figure 2.13 shows the basic configuration of the PLL system [54].

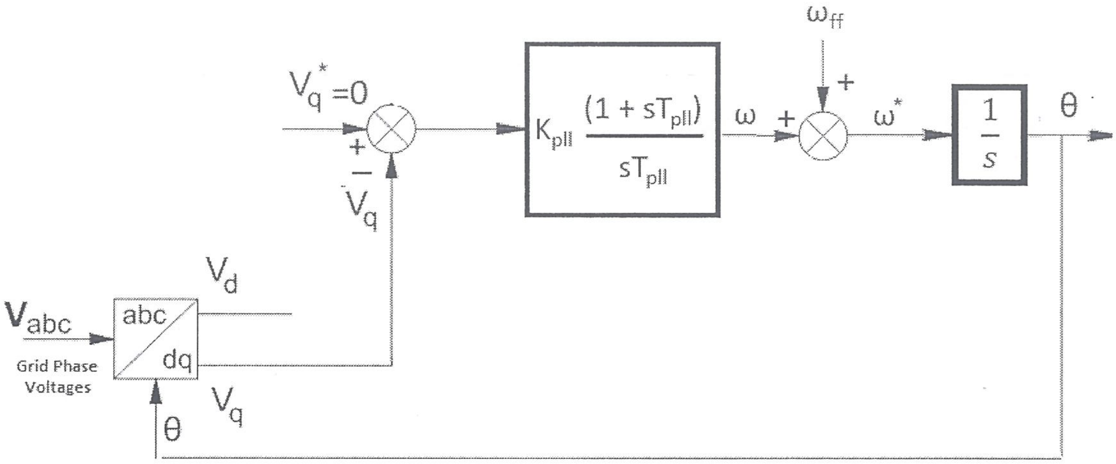

Figure 2.13: Control diagram of the phase-locked loop

2.7.3 PI Current Controller

Traditionally, DC/AC converters used in distributed power system behave as a current source when they are connected to the grid [55]. Up to now, most grid-tied DC/AC converters adopt the voltage source inverter topology with a current controller to adjust and regulate the current injected to the grid [56-58]. Current-controlled grid-tied inverters have very good dynamics to handle the variation in the grid. Furthermore, they also have the advantages of the high-accuracy instantaneous current control, overload rejection and peak-current protection. The performance of a voltage-source grid-tied DC/AC converters depends on the quality of the implemented current controller [59]. Additionally, a well implemented current controller rises the current harmonic performance of DC/AC converter and these grid-tied inverters have very good capability in harmonic rejection [59]. Therefore, the DC/AC converter can meet the power quality requirements [17].

The current controller should be designed with different strategies like PI controller, proportional-resonant (PR) controller, predictive deadbeat (DB), e.g. [60].

The PI current controller is commonly used and can work well system. The PI current controller scheme in the synchronously rotating (d, q) reference frame [59].

The closed loop current controller for d synchronous rotating frame structure is given in Figure 2.14. Figure 2.15 also shows the basic internal structure of a grid-tied DC/AC converter current controller.

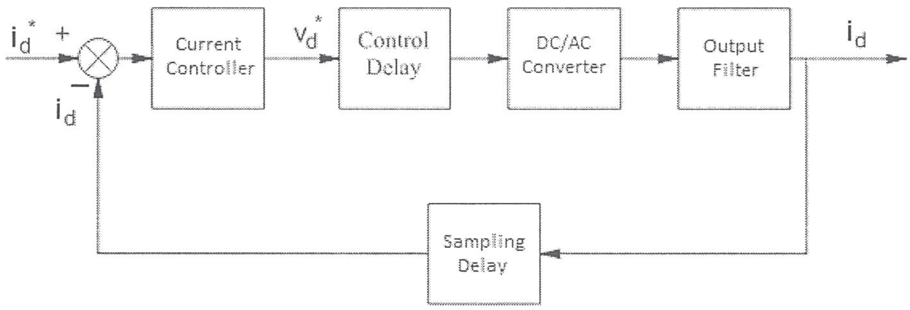

Figure 2.14: Closed-loop current controller

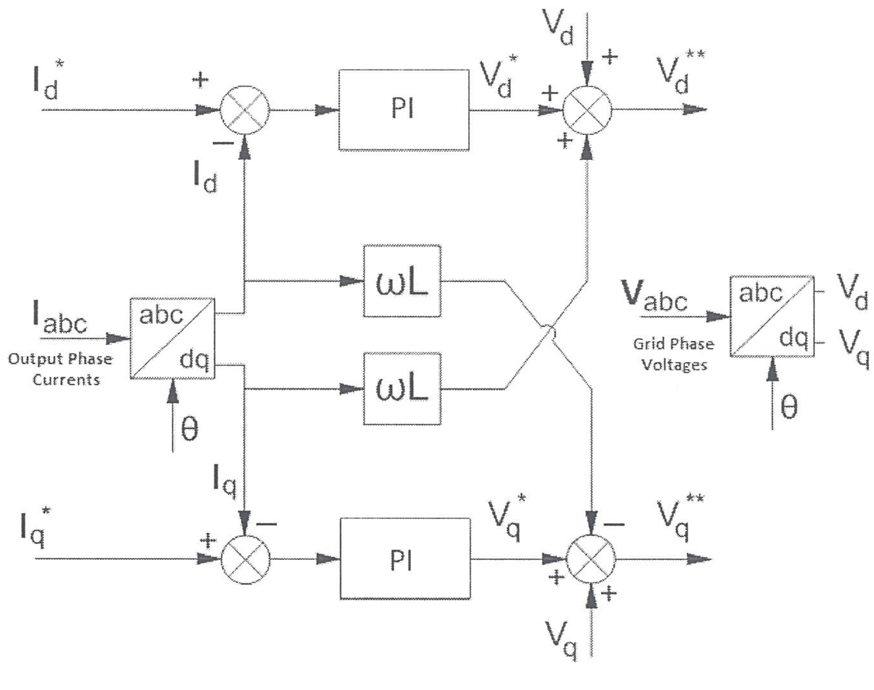

Figure 2.15: Control diagram of PI current controller

2.7.4 PR Current Controller

The PR control scheme in the stationary frame (α, β) is another popular current controller technique. Because PR current controller has the capability of eliminating the steady-state error while regulating the sinusoidal signals. PR current controller can also compensate multiple harmonics [59]. Therefore, PR current controller is generally used as an auxiliary current controller to compensate low order harmonic current ripple like 5^{th}, 7^{th}, 11^{th}, 13^{th} harmonics because of the heavy harmonic limits of the power systems [17]. The transfer function of the PR current controller is given in (35).

$$G_{PR} = \frac{2K_{im} \cdot s}{s^2 + (m\omega_e)^2} \tag{35}$$

where

K_{im}	is the integral gain of the controller.
m	is the frequency coefficient
ω_e	is the angular fundamental frequency

The PR current controllers are designed for a specific frequency. Therefore, there are more than one PR controllers in a grid-tied inverter. The PR controller can also be implemented in synchronously rotating (d, q) reference frame for a grid-tied DC/AC converter if it is used for eliminating the low order harmonics. For example, if PR controller is implemented to eliminate 6^{th} harmonic in synchronously rotating (d, q) reference frame, PR controller can eliminate 5^{th}, 7^{td} in the stationary frame. The PR current controllers at 6ω and 12ω with PI current controller are shown in Figure 2.16 in synchronously rotating reference frame.

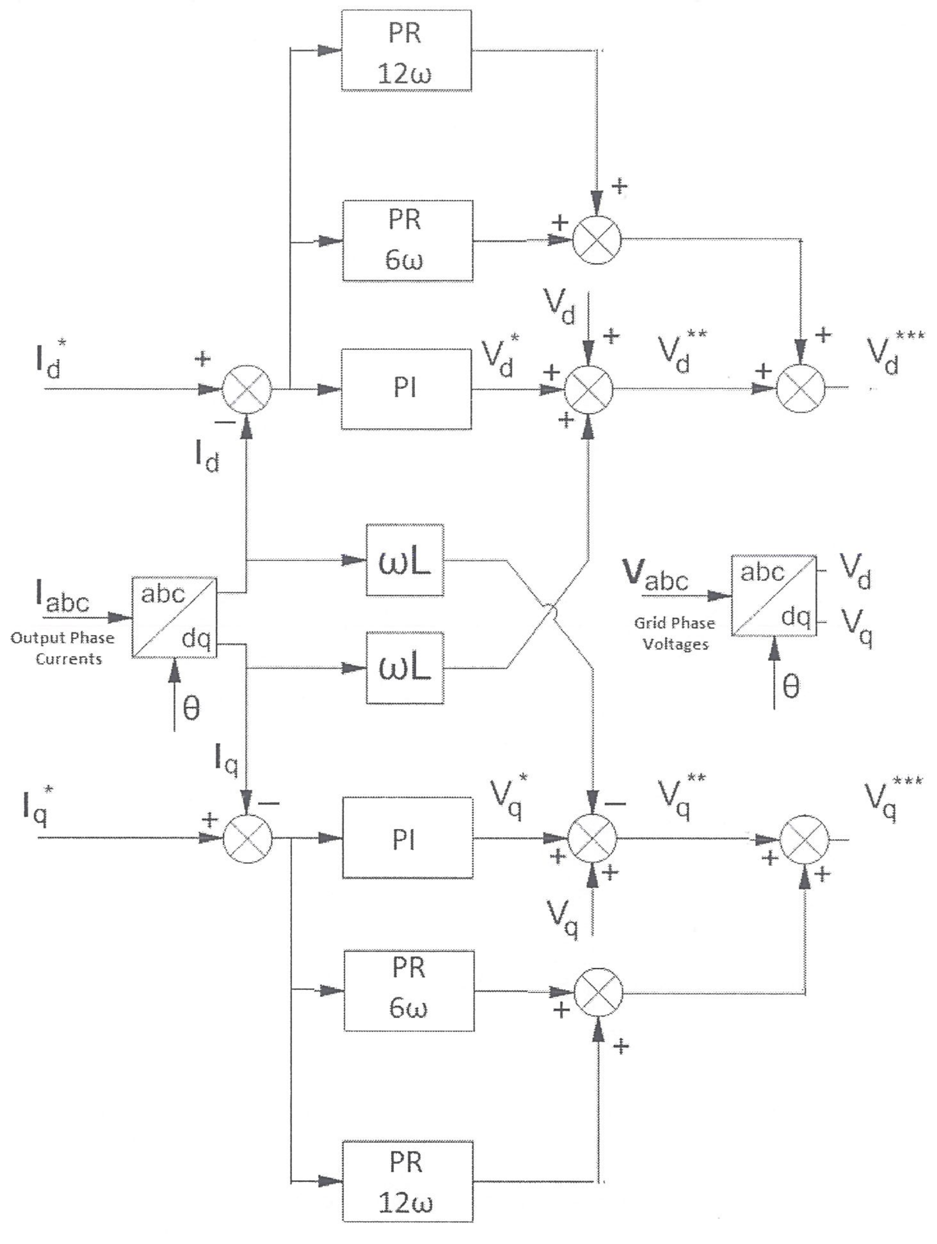

Figure 2.16: Control diagram of PR current controller

2.7.5 Voltage Controller

The function of the voltage controller is to regulate the DC-Link at the desired value. The control objectives of a voltage controller are as follows [61]:

- The average value of the DC-Link voltage must track its reference or target voltage with zero steady state error.
- Voltage controller should minimize the fluctuations of the DC-Link voltage after the sudden changes of the active injected power.
- The DC/AC converter output (grid) current is also related to the stability of the voltage controller outputs. Therefore, the grid current must be prevented from additional harmonic contents and instability.

The Figure 2.17 presents the closed-loop voltage controller.

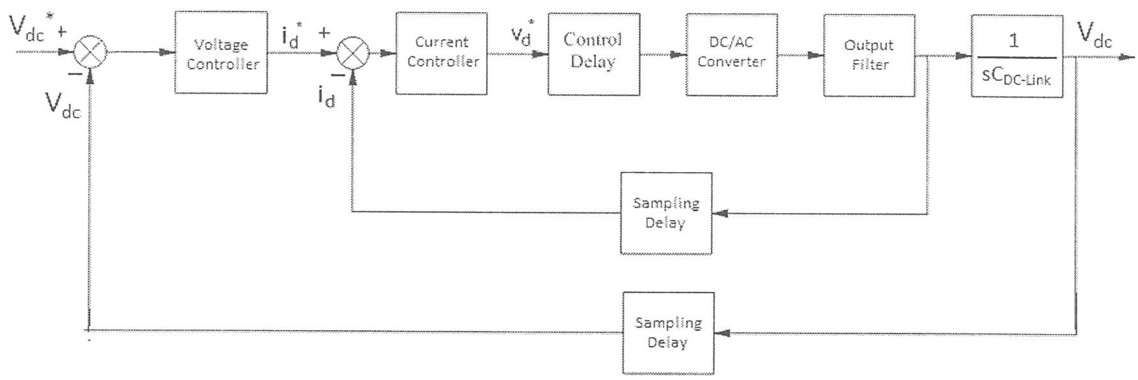

Figure 2.17: Closed-loop voltage controller

2.7.6 General Control Schematic of Grid-Tied DC/AC Converter

The general control schematic of grid-tied DC/AC converter is given in Figure 2.17.

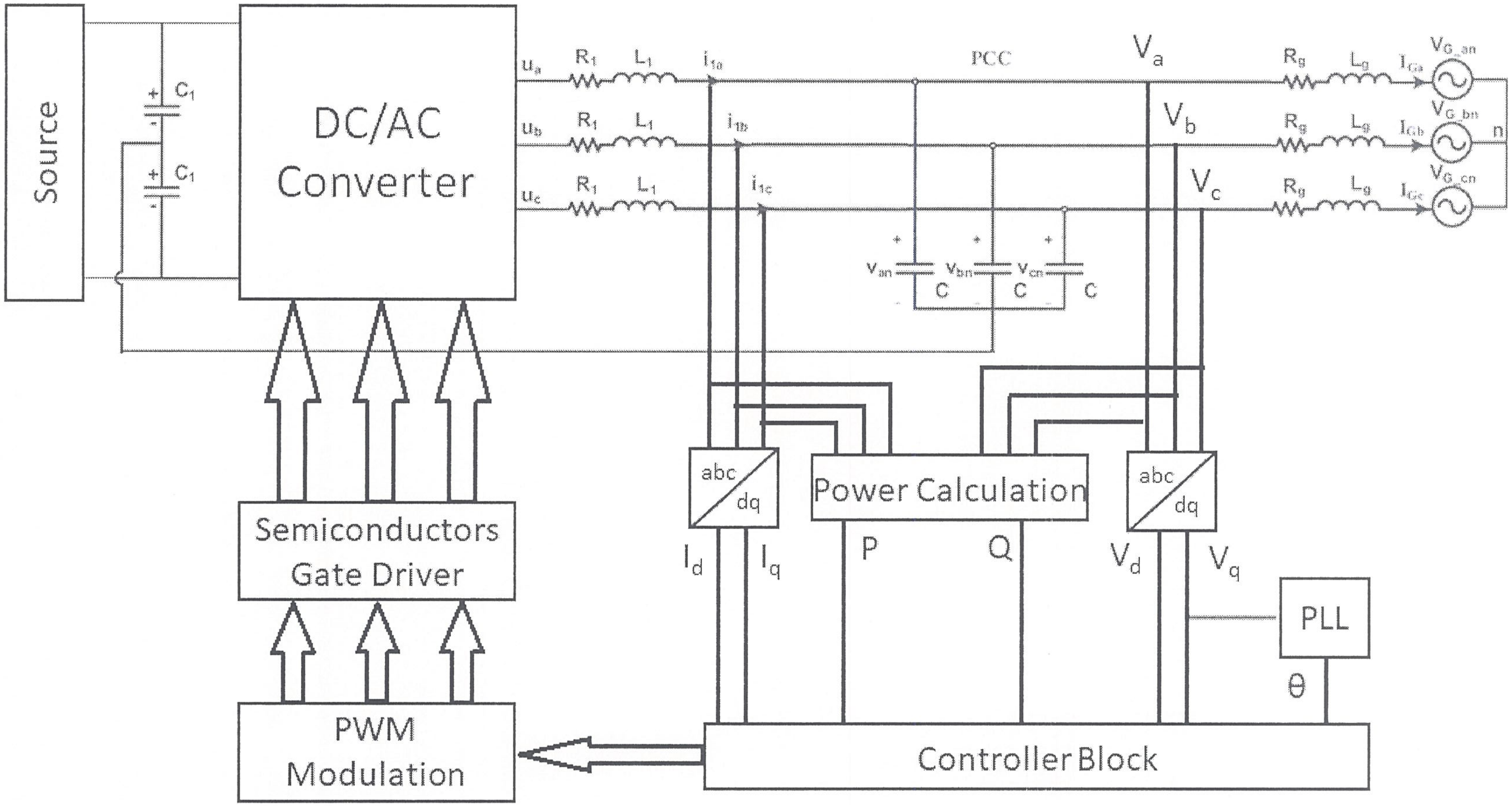

Figure 2.18: General schematic of grid-tied DC/AC converter

2.8 *Unbalance Voltage Compensator*

In section 2.2, the cause of the grid voltage unbalance and symmetrical components of the grid are discussed. Especially, the grid-tied inverter DC-Link capacitors are affected by unbalanced grid voltage. Second-order harmonics ripple currents flow on the DC-Link capacitor during grid voltage unbalance [7]. Furthermore, the output current harmonic ripple characteristic also changes during the unbalance voltage conditions. In [7, 8], a unbalance voltage compensator is introduced to eliminate the negative effects of the unbalanced grid conditions. If zero sequence term of grid symmetrical components is neglected (24-26) can be rewritten as (36-38) [7].

$$V_a = V_{a+}\cos(\omega t + \alpha) + V_{a-}\cos(\omega t + \beta) \tag{36}$$

$$V_b = V_{b+}\cos(\omega - 120^\circ t + \alpha) + V_{b-}\cos(\omega t + 120^\circ + \beta) \tag{37}$$

$$V_c = V_{c+}\cos(\omega + 120^\circ t + \alpha) + V_{c-}\cos(\omega t - 120^\circ + \beta) \tag{38}$$

After clarke transform, (36-38) can be written as space vector form (39). Furthermore, in a similar way, unbalanced currents which flow into a the grid can be written as (40) [7].

$$V_s = V_{pm}e^{j(\omega t+\alpha)} + V_{nm}e^{-j(\omega t+\alpha)} \tag{39}$$

$$I_s = I_{pm}e^{j(\omega t+\alpha)} + I_{nm}e^{-j(\omega t+\alpha)} \tag{40}$$

where

V_s	space vector form of the line voltages.
V_{pm}	positive sequence term of V_s.
V_{nm}	negative sequence term of V_s.
I_s	space vector form of the line currents.
I_{pm}	positive sequence term of I_s.
I_{nm}	negative sequence term of I_s.

By replacing (39) and (40) into (12), the instantaneous power can be obtained. In (12), the dot product terms between the positive and negative symmetrical components of voltage and current generate 2ω frequency power ripple as (41). DC-Link voltage ripple is the result of 2ω frequency power ripple.

$$P + jQ = V_s \cdot I_s^* =$$
$$(V_{pm}I_{pm}e^{j(\alpha-\lambda)} + V_{nm}I_{nm}e^{-j(\beta-\gamma)}) + (V_{pm}I_{nm}e^{j(2\omega t+\alpha+\gamma)} + V_{nm}I_{pm}e^{-j(2\omega t+\beta-\lambda)}) \quad (41)$$

From (41), the required negative sequence injected current can be extracted as (42) [7].

$$I_{nm} = -\frac{V_{nm}}{V_{pm}}I_{pm} \text{ and } \gamma = \beta - \alpha - \lambda \quad (42)$$

Active and reactive power can be defined as (43) in the instantaneous power theory [62].

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} \bar{P} \\ \bar{Q} \end{bmatrix} + \begin{bmatrix} \tilde{P} \\ \tilde{Q} \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} \bar{I}_\alpha + \tilde{I}_\alpha \\ \bar{I}_\beta + \tilde{I}_\beta \end{bmatrix} \quad (43)$$

where

$\bar{P}, \bar{Q}$	are the active and reactive power DC terms.
$\tilde{P}, \tilde{Q}$	are the active and reactive power ac ripple terms
V_α, V_β	are the clarke transformed three-phase grid voltages
$\bar{I}_\alpha, \bar{I}_\beta$	are the currents which make constant power
$\tilde{I}_\alpha, \tilde{I}_\beta$	are the currents which are perturbing power

If the power ripple $\tilde{P}$ and $\tilde{Q}$ are inversely transformed, $\tilde{I}_\alpha$ and $\tilde{I}_\beta$, which perturb the power because of unbalanced grid voltage, can be extracted from (43) as follows:

$$\begin{bmatrix} \tilde{I}_\alpha \\ \tilde{I}_\beta \end{bmatrix} = -\begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix}^{-1} \begin{bmatrix} P - \bar{P} \\ Q - \bar{Q} \end{bmatrix} = -\begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix}^{-1} \begin{bmatrix} \tilde{P} \\ \tilde{Q} \end{bmatrix} \quad (44)$$

Under the assumption that grid voltages are sinusoidal functions, active power is defined in (7) and reactive power can be defined as follows [7]:

$$Q = U_a(t)I_a(t) + U_b(t)I_b(t) + U_c(t)I_c(t) \tag{45}$$

where

$U_a(t) = \sqrt{2}V\cos(\omega t)$

$U_b(t) = \sqrt{2}V\cos(\omega t - 120^{\circ)}$

$U_c(t) = \sqrt{2}V\cos(\omega t + 120^{\circ)}$

The injected unbalance compensation currents $\tilde{I}_\alpha$ and $\tilde{I}_\beta$ can be obtained from the compensation of (44) and (45) as follows:

$$\begin{bmatrix} \tilde{I}_\alpha \\ \tilde{I}_\beta \end{bmatrix} = \frac{1}{V_\alpha U_\beta - U_\alpha V_\beta} \begin{bmatrix} U_\beta & -V_\beta \\ -U_\alpha & V_\alpha \end{bmatrix} \begin{bmatrix} P - \bar{P} \\ Q - \bar{Q} \end{bmatrix} \tag{46}$$

The updated general schematic of grid-tied DC/AC converter with unbalance compensation controller is given in Figure 2.19.

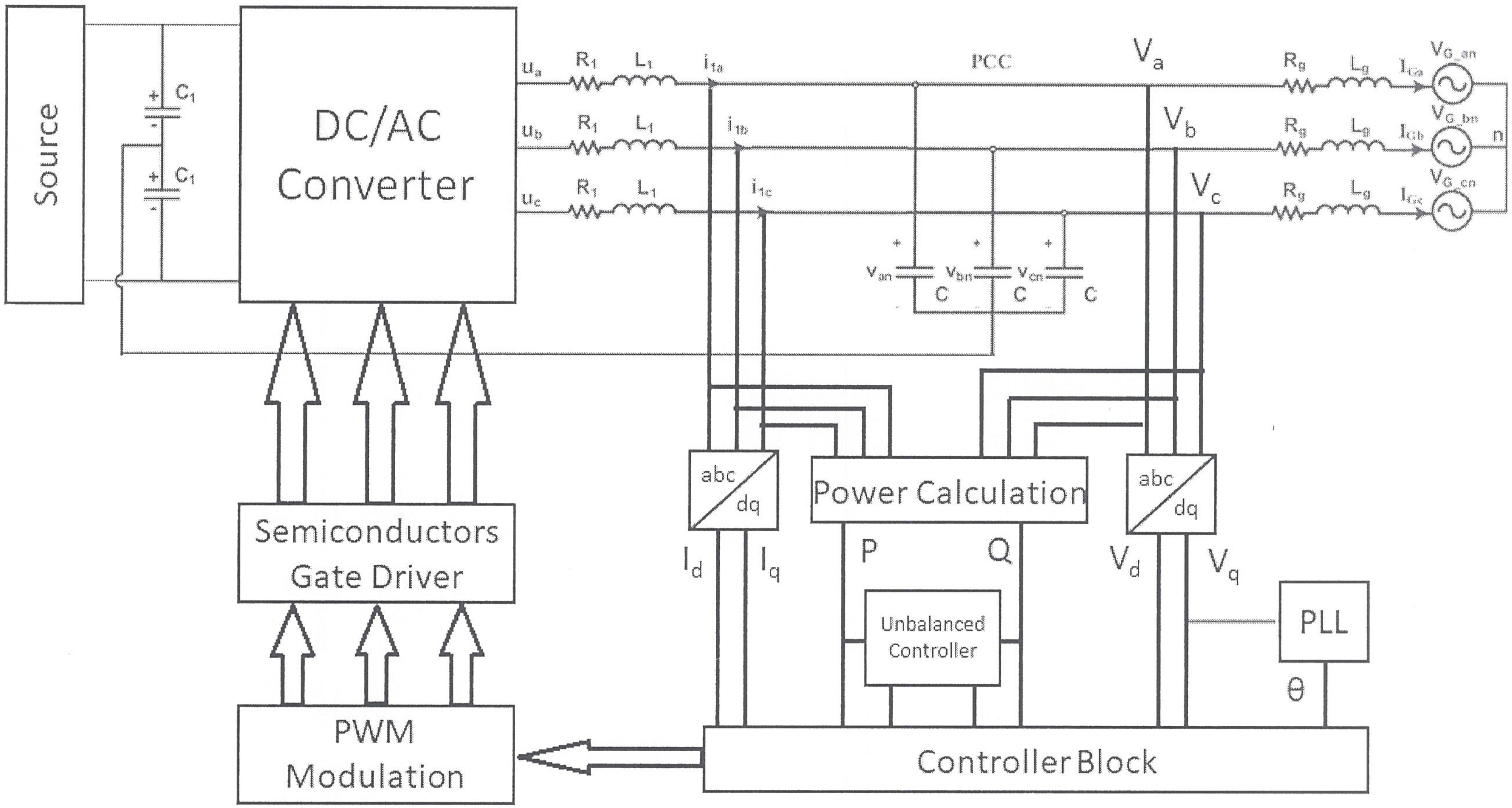

Figure 2.19: General schematic of grid-tied DC/AC converter with unbalance controller

CHAPTER III

SYSTEM MODELING

This chapter presents the implementation of 10kVA grid-tied DC/AC converter in simulation software PLECS. The 10kVA grid-tied DC/AC converter system model is illustrated in Figure 3.1. Generally, a grid-tied DC/AC converter system includes DC-Link capacitors, a semiconductor switching block, and a filter block. The DC/AC converter is modelled as 3L-NPC converter topology because of the advantages that are described in [43, 44]. The filter block is modelled as an LC filter and it consists of a filter inductor and a filter capacitance. The specifications of the DC/AC converter operation are given in Table 3.1.

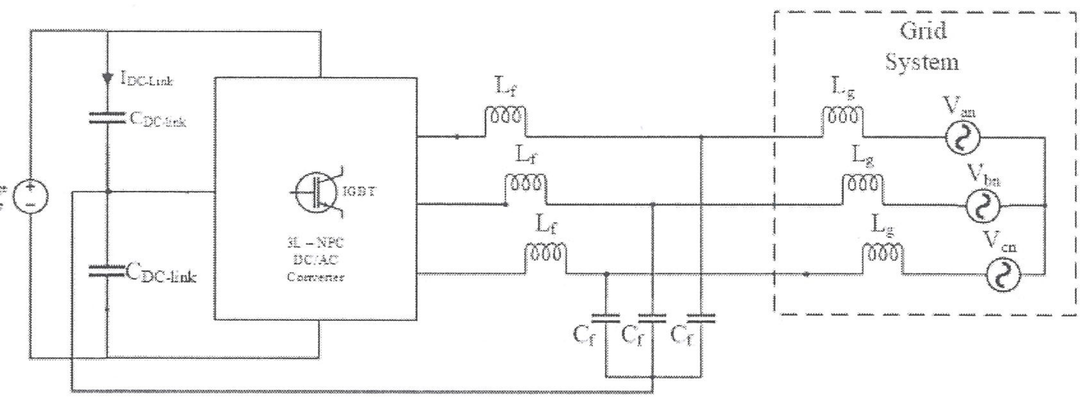

Figure 3.1: Three-phase grid-tied DC/AC converter model

The filter inductance is an important parameter for the output current THD [63, 64]. The ripple on the output current is directly related with the filter inductance, switching frequency and DC-Link voltage [63]. The filter inductance L_f can be calculated as (47). In order to find a good estimation on the filter inductance, four different DC-Link voltages are used to calculate the filter inductance while $\Delta I_{ph(max)}$ is set to 15%: 900V, 800V, 700V, and 600V. The calculated inductances based on

Table 3.1: 10 kVA grid-tied DC/AC converter operation specification

Measures	Quantity (Unit)
S_{max}	10 kVA
$V_{DC_{Max}}$	1000V
f_s	16 kHz
$V_{grid(l-l)}$	400 Vrms
C_f	8 μF

DC-Link voltages are given in Table 3.2. Higher filter impedance provides better output current THD ratio. However, higher filter inductance also causes a higher voltage drop on inductance and makes control more difficult than usual [64]. Thus, the filter inductance for the simulation model is selected as 800 μH. Furthermore, the corner frequency of LC filter f_{corner} is equal to 2 kHz at 8 μF filter capacitance and 800 μH filter inductance. Because the switching frequency of a DC/AC converter should be equal to minimum 8 times more than the corner frequency of output filter for a good harmonic current spectrum at the output of the converter.

$$L_f = \frac{V_{DC}}{16 \cdot f_s \cdot \Delta I_{ph(max)}} \tag{47}$$

where

V_{DC} is the DC-Link voltage

f_S is the DC/AC converter switching frequency

$\Delta I_{ph(max)}$ is the maximum peak-to-peak grid current ripple

Table 3.2: Filter inductance based on different DC-Link voltages

DC-Link Voltage V_{DC}	**Filter Inductance, L_f**
900V	879 μH
800V	781 μH
700V	684 μH
600V	586 μH

The grid is modeled as a 600 kVA distribution transformer. The typical rated impedance of a 600 kVA distribution transformer is 6% [65]. The leakage inductance L_g of distribution transformer is calculated as 100 μH and it is used as the grid leakage inductance in simulations [66].

The control and modulation techniques of a DC/AC converter are discussed in section 2.7 and 2.6. For this system, the space vector modulation technique (SVPWM) is used because of its high linear working range and advantages that placed in [43, 44]. SVPWM provides to DC/AC converter operates at 600V. Furthermore, this simulation model has voltage, power and current controller to regulate DC/AC converter internal and external dynamics. Power and voltage regulators have PI controller. The current regulator has PI and PR controller to make sure the system stability. All controllers gains are calculated in MATLAB Single-Input Single-Output (SISO) tool.

3.1 DC-Link Capacitor Model

DC-Link capacitor types and features are discussed in section 2.3. The DC-Link capacitor is modeled in two different types: **i)** Film capacitor (TDK - B32776G5506K000), **ii)** Electrolytic capacitor (TDK - B43544A6477M0)

In this thesis, the total volume of a DC-Link capacitor is kept constant. The number of each DC-Link capacitor block is determined by the DC-Link capacitor ripple current. Firstly, the electrolytic capacitor is selected and the total volume that is covered by the electrolytic capacitor is determined because of the low ripple current capability. Then, a film capacitor is selected in the market and the number of the film capacitor is determined by the same volume. The necessary electrolytic capacitor value for each DC-Link capacitor block is set as 1880 μF according to DC-Link capacitor ripple current ratio [43]. A film capacitor is selected by the consideration of the total volume of the electrolytic capacitor block. The detailed information about the electrolytic and film capacitor is given in Table 3.3 [67, 68]. Furthermore, a DC-Link capacitor block is illustrated in Figure 3.2 and Figure 3.3, which show electrolytic and film capacitor respectively. The capacitance of each DC-Link block is set to 200 μF with the film capacitors. The equivalent capacitance of DC-Link is achieved 940 μF and 100 μF with electrolytic and film capacitors respectively.

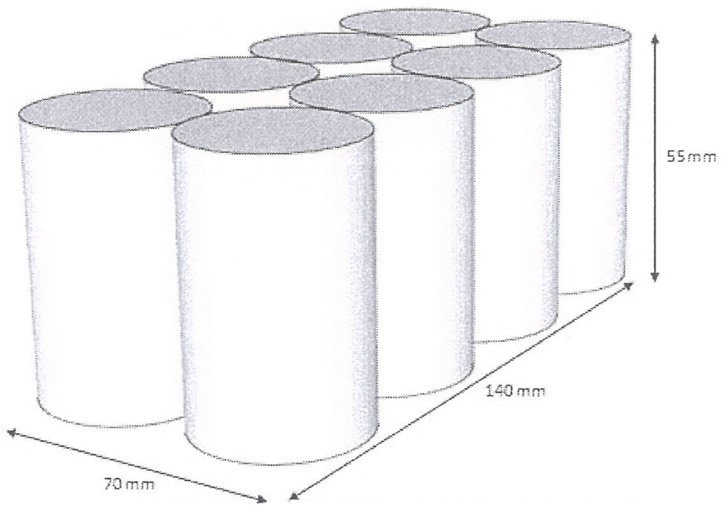

Figure 3.2: DC-Link Model with Electrolytic Capacitor

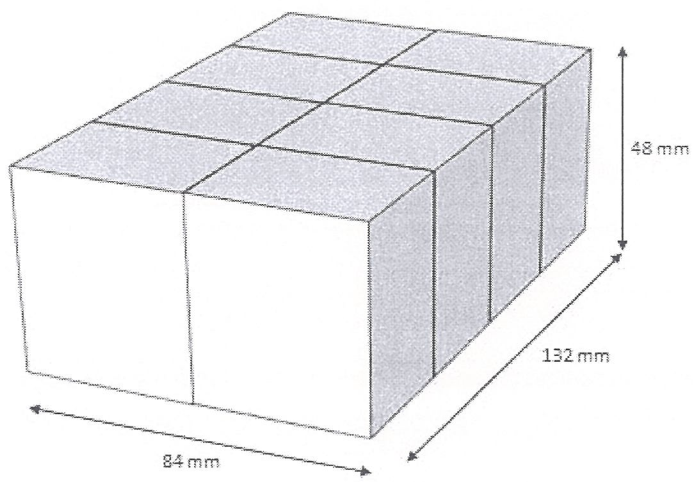

Figure 3.3: DC-Link Model with Film Capacitor

Table 3.3: DC-Link capacitors

Capacitor Type Brand Code	Capacitance	Size of Each Capacitor	Total Volume of DC-Link Block	Total Capacitance of DC-Link Block
Electrolytic Capacitor – TDK B43544A6477M0	470 μF	35x55 mm	$\approx$ 539 cm^3	940 μF
Film Capacitor – TDK B32776G5506K000	50 μF	33.0×48.0×42.0 mm	$\approx$ 532 cm^3	100 μF

3.2 *Grid Conditions*

This study is about to observe the dynamics of a grid-tied DC/AC converter under eight unbalanced grid conditions for two different DC-Link capacitor types. One of those conditions is a balanced grid, and the others are unbalanced grid conditions that are chosen as magnitude deformation. Therefore, there is no phase angle distortion.

- **Grid Condition 1:** Balanced three-phase voltage (Figure 3.4).

- **Grid Condition 2:** V_a increases 10% of nominal voltage, V_b and V_c remain stable (Figure 3.5).

- **Grid Condition 3:** V_a decreases 10% of nominal voltage, V_b and V_c remain stable (Figure 3.6).

- **Grid Condition 4**: V_a decreases 10% of nominal voltage, V_b increases 10% of nominal voltage and V_c remains stable (Figure 3.7).

- **Grid Condition 5:** V_a and V_b decrease 10% of nominal voltage, and V_c remains stable (Figure 3.8).

- **Grid Condition 6:** V_a and V_b increase 10% of nominal voltage, and V_c remains stable (Figure 3.9).

- **Grid Condition 7:** V_a decreases 20% of nominal voltage, V_b and V_c remain stable (Figure 3.10).

- **Grid Condition** 8: V_a, V_b and V_c decrease 10% of nominal voltage (Figure 3.11).

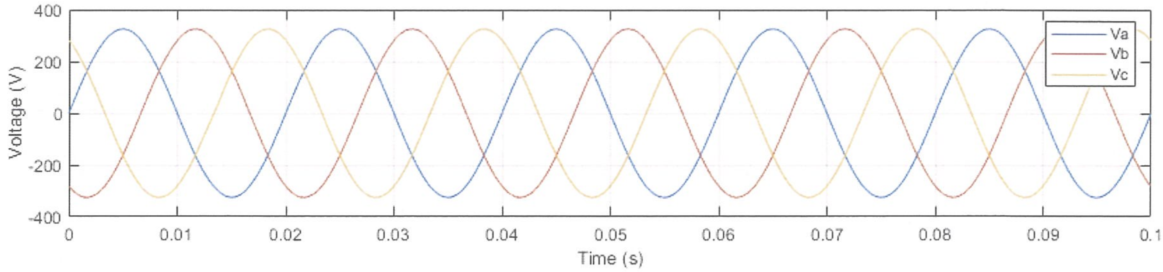

Figure 3.4: Grid condition 1

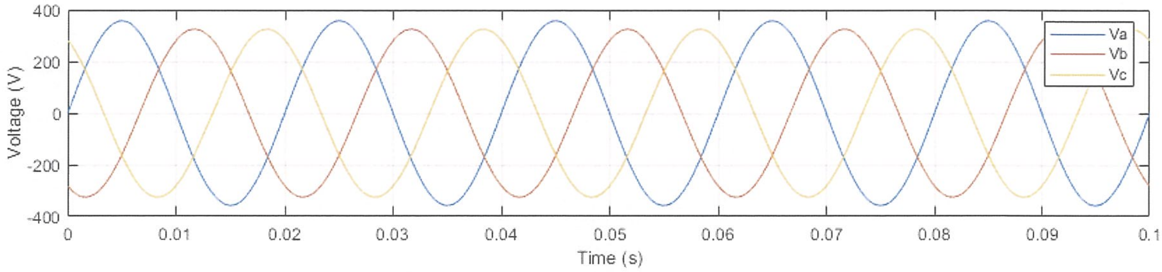

Figure 3.5: Grid condition 2

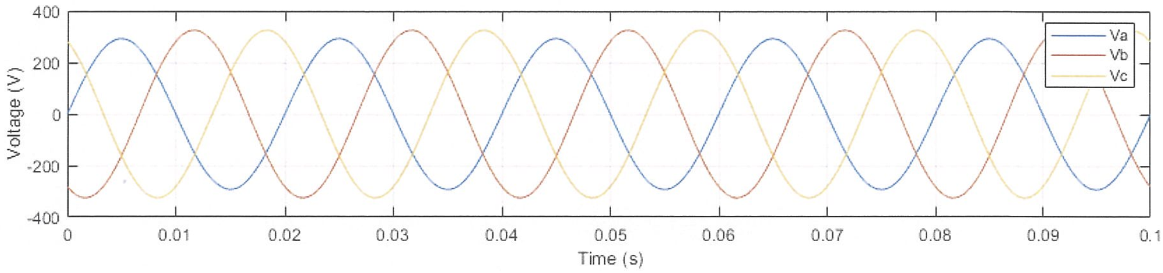

Figure 3.6: Grid condition 3

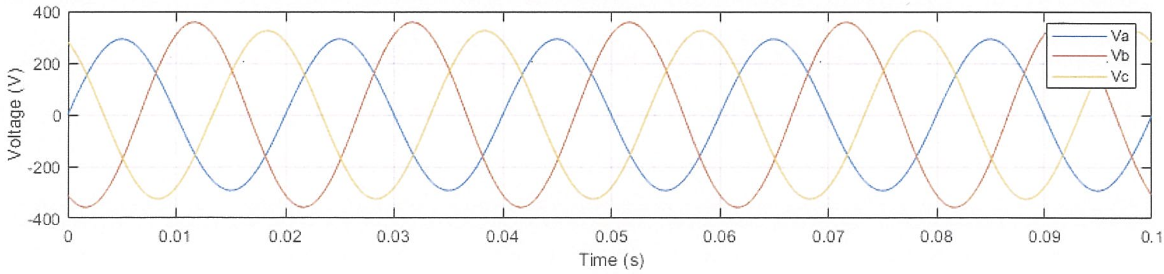

Figure 3.7: Grid condition 4

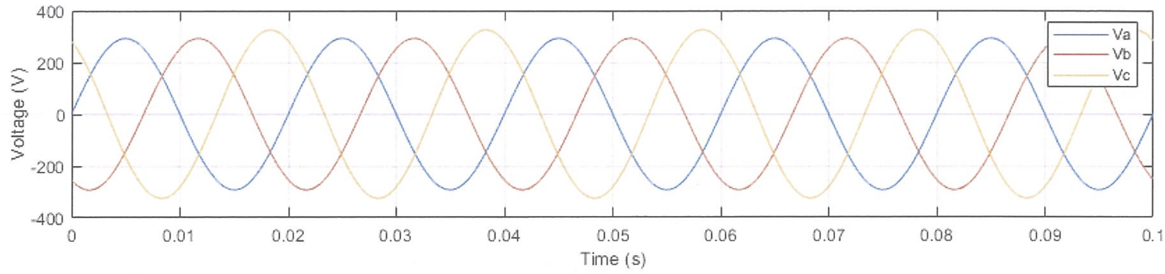

Figure 3.8: Grid condition 5

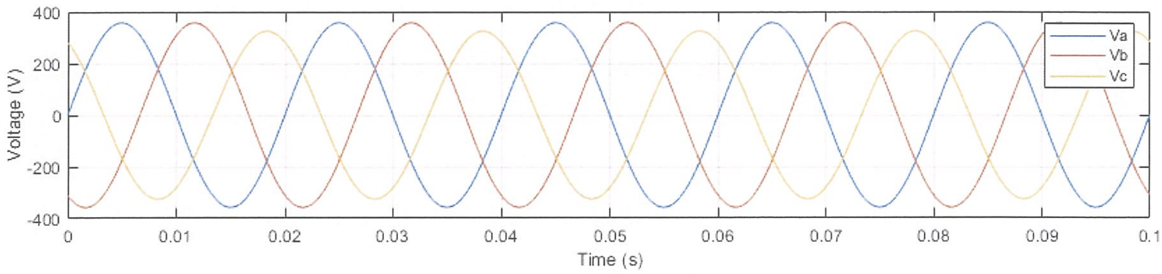

Figure 3.9: Grid condition 6

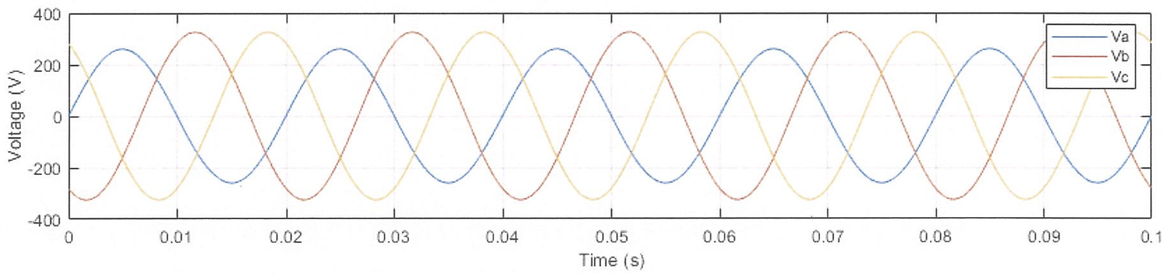

Figure 3.10: Grid condition 7

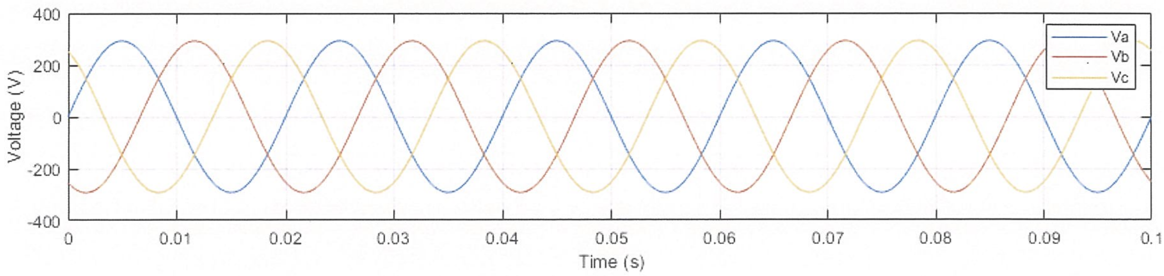

Figure 3.11: Grid condition 8

CHAPTER IV

RESULTS

In order to examine the impacts of the type of a DC-Link capacitor, a computer simulation program, PLECS, is carried out on a 10 kVA grid-tied DC/AC converter. In Figure 4.1, all simulation model is given.

One of the variables of the simulation is the grid condition. Eight grid conditions are implemented to the simulations to observe the effects on internal and external dynamics of 10 kVA grid-tied inverter.

Furthermore, four DC-Link voltage levels are selected for simulations: 900V, 800V, 700V, and 600V. Furthermore, the effect of power factor on DC/AC converter output current THD is observed. For that purpose, there are five power factor situations, which are 0.60 lagging, 0.80 lagging, 0.60 leading, 0.80 leading, and 1, are implemented. On the other hand, all simulations are repeated with the implementation of an unbalanced controller to the simulation model.

The simulation model is carried out with a discrete-time controller. For that purpose, the C-Block in PLECS is used in the simulation model. In, Figure 4.1, the discrete-time controller inputs and outputs in the simulation model is also given.

In this chapter, the output current harmonic characteristics and output current THDs are given. DC-Link capacitor ripple current components also state in this chapter. All results are given for two types of DC-Link capacitor. Additionally, the DC-Link capacitor lifetime expectations are calculated and given for electrolytic DC-Link capacitor block.

Furthermore, the effects of the unbalance controller on output current and DC-Link capacitor current and lifetime expectations are investigated in this chapter.

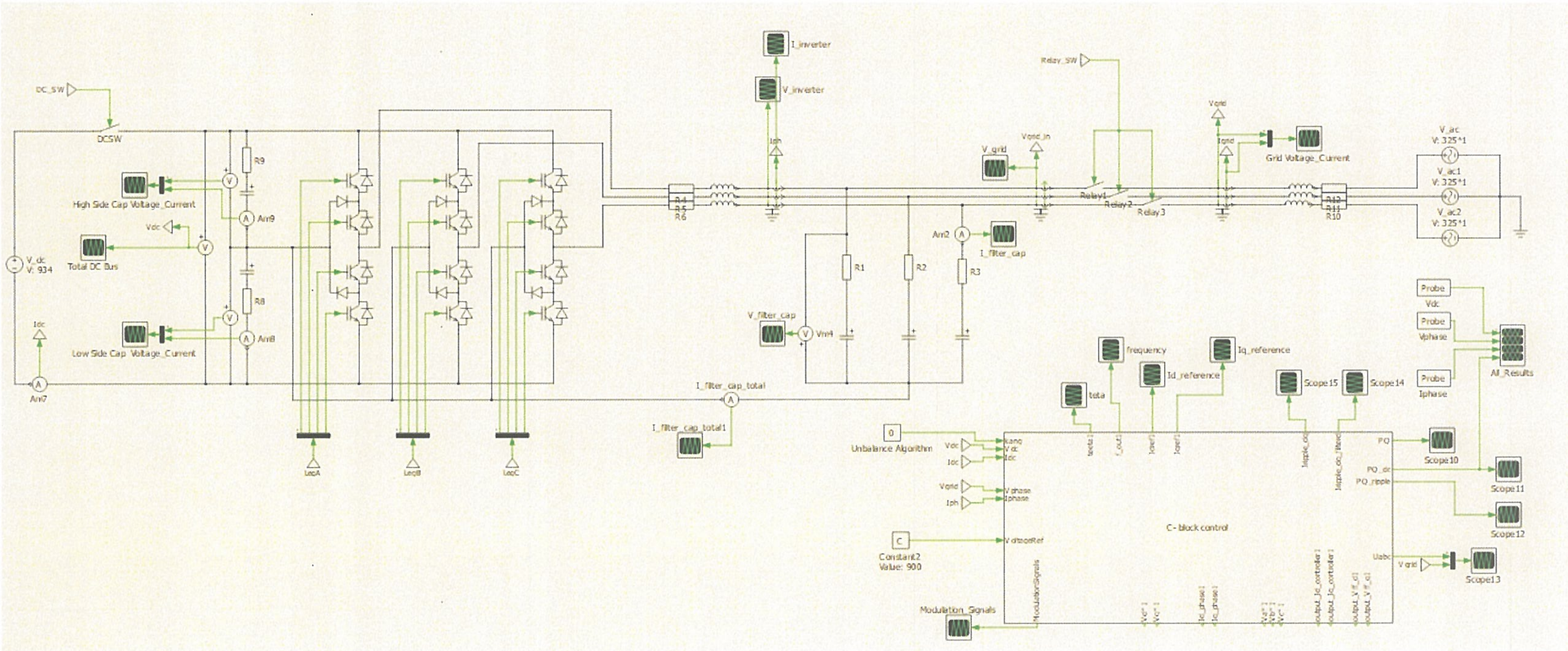

Figure 4.1: Simulation Model

Most of the DC/AC converters are design to work in the linear region. However, there are too many variables in the simulations. Therefore, the linearity of the inverter must be checked. One of the easy ways to check the linearity of the inverters is the modulation index.

The SVPWM modulation technique is implemented in this simulation and the theoretical limit of the linearity region is approximately 1.047 [69]. For 3L SVPWM modulation technique, the modulation index m_i can be calculated as follows:

$$m_i = \frac{V_{1m}}{\frac{2V_{DC}}{\pi}} \tag{48}$$

where

V_{1m} is the fundamental component magnitude of the line to neutral inverter output voltage.

Table 4.1 - Table 4.4 show the modulation index of DC/AC converter with electrolytic capacitor block for 900V, 800V, 700V and 600V DC-Link voltages respectively. Furthermore, Table 4.5 - Table 4.8 show the modulation index of DC/AC converter with film capacitor block for 900V, 800V, 700V and 600V DC-Link voltages respectively.

Table 4.1: Modulation Index with Electrolytic Capacitors at 900V

Power Factor	**Grid Conditions**							
	1	2	3	4	5	6	7	8
-0.6	0.618	0.65	0.618	0.65	0.587	0.681	0.619	0.556
-0.8	0.62	0.653	0.622	0.652	0.591	0.684	0.622	0.558
1	0.628	0.66	0.628	0.66	0.598	0.69	0.628	0.565
0.8	0.635	0.666	0.634	0.66	0.604	0.697	0.634	0.572
0.6	0.636	0.667	0.636	0.667	0.606	0.698	0.636	0.573

Table 4.2: Modulation Index with Electrolytic Capacitors at 800V

Power Factor	Grid Conditions							
	1	2	3	4	5	6	7	8
-0.6	0.696	0.732	0.696	0.731	0.66	0.766	0.696	0.626
-0.8	0.697	0.735	0.699	0.734	0.665	0.769	0.699	0.629
1	0.706	0.742	0.706	0.741	0.672	0.776	0.706	0.636
0.8	0.714	0.749	0.714	0.748	0.68	0.784	0.713	0.644
0.6	0.716	0.751	0.715	0.75	0.681	0.786	0.715	0.645

Table 4.3: Modulation Index with Electrolytic Capacitors at 700V

Power Factor	Grid Conditions							
	1	2	3	4	5	6	7	8
-0.6	0.795	0.836	0.795	0.836	0.757	0.876	0.796	0.715
-0.8	0.798	0.84	0.799	0.839	0.76	0.88	0.8	0.718
1	0.806	0.848	0.807	0.846	0.768	0.887	0.807	0.726
0.8	0.815	0.857	0.815	0.855	0.777	0.895	0.815	0.735
0.6	0.818	0.859	0.817	0.857	0.779	0.898	0.817	0.737

Table 4.4: Modulation Index with Electrolytic Capacitors at 600V

Power Factor	Grid Conditions							
	1	2	3	4	5	6	7	8
-0.6	0.927	0.975	0.928	0.975	0.883	1.083	0.929	0.834
-0.8	0.931	0.98	0.932	0.979	0.887	1.107	0.933	0.838
1	0.941	0.989	0.941	0.987	0.897	1.168	0.942	0.847
0.8	0.951	1	0.951	0.997	0.906	1.244	0.951	0.858
0.6	0.954	1.003	0.953	1	0.909	1.246	0.953	0.86

Table 4.5: Modulation Index with Film Capacitors at 900V

Power Factor	Grid Conditions							
	1	2	3	4	5	6	7	8
-0.6	0.619	0.65	0.618	0.649	0.588	0.681	0.618	0.556
-0.8	0.611	0.653	0.621	0.652	0.591	0.683	0.621	0.559
1	0.627	0.659	0.628	0.659	0.597	0.69	0.627	0.565
0.8	0.634	0.666	0.634	0.666	0.603	0.697	0.634	0.572
0.6	0.636	0.668	0.636	0.668	0.605	0.698	0.636	0.573

Table 4.6: Modulation Index with Film Capacitors at 800V

Power Factor	Grid Conditions							
	1	2	3	4	5	6	7	8
-0.6	0.696	0.731	0.696	0.731	0.662	0.766	0.695	0.626
-0.8	0.699	0.773	0.699	0.734	0.665	0.769	0.698	0.629
1	0.706	0.741	0.706	0.741	0.671	0.776	0.705	0.636
0.8	0.713	0.749	0.713	0.749	0.68	0.783	0.713	0.643
0.6	0.715	0.751	0.715	0.751	0.68	0.785	0.715	0.645

Table 4.7: Modulation Index with Film Capacitors at 700V.

Power Factor	Grid Conditions							
	1	2	3	4	5	6	7	8
-0.6	0.795	0.835	0.795	0.835	0.756	0.875	0.795	0.715
-0.8	0.798	0.839	0.798	0.838	0.759	0.878	0.798	0.718
1	0.807	0.847	0.806	0.847	0.767	0.886	0.806	0.726
0.8	0.815	0.856	0.815	0.856	0.775	0.895	0.815	0.735
0.6	0.817	0.858	0.817	0.858	0.777	0.897	0.818	0.737

Table 4.8: Modulation Index with Film Capacitors at 600V

Power Factor	Grid Conditions							
	1	2	3	4	5	6	7	8
-0.6	0.927	0.975	0.927	0.975	0.881	1.059	0.927	0.834
-0.8	0.931	0.979	0.931	0.979	0.885	1.073	0.931	0.838
1	0.941	0.988	0.941	0.988	0.895	1.111	0.94	0.847
0.8	0.95	0.998	0.95	0.999	0.904	1.161	0.951	0.857
0.6	0.952	1	0.953	1.002	0.906	1.177	0.953	0.859

4.1 Output Current Harmonics and THD without Unbalance Controller

The output current THD and current harmonics are observed to validate the differences between two capacitor types without unbalance controller.

4.1.1 Electrolytic DC-Link Capacitor

The output grid currents of DC/AC converter are given in Table 4.9 - Table 4.12 with respect to the DC-Link voltage. Furthermore, the DC/AC converter output current THDs are given in Table 4.13 - Table 4.20. The DC/AC converter output current THDs also given in Figure 4.2 - Figure 4.9 in 3D form to visualize the structure.

In the balanced system as shown in Figure 4.2, the output current THD is under 1.3% for all dc voltage variations and power factor variations. The worst current THD in all grid conditions is observed in 600V DC-Link voltage and 0.6 lagging power factor.

The output current THD is affected negatively when the power factor is either lagging or leading. A lagging operation affects the current THD more than a leading operation for the same power factor

All unbalanced grid conditions, except the eighth condition, have a negative effect on output current THD. There is one hazardous result in the current THD, which is given in grid condition 6. Due to the voltage increase in the two phases of the grid, the DC/AC converter enters to a nonlinear modulation region and the output current THD goes up to 41% at 600V DC-Link voltage. Therefore, this condition is neglected in Figure 4.7. The output current THD is under 2.25%, and it is in the linear modulation region of the converter. Maximum current THD is observed as 2.25% in the grid condition 7 at 600V DC voltage and 0.6 lagging power factor. The DC/AC converter can handle the unbalanced grid condition without any deflection from the THD standards of a grid-connected converter.

According to IEEE 519-2014, the output current THD of the DC/AC converter is limited to 5% [17]. Therefore, an electrolytic DC-Link capacitor block can handle unbalanced conditions without losing the control ability of the DC/AC converter.

There is an inverse proportion between a DC-Link voltage and an output current THD ratio. A DC-Link voltage is directly related to output current THD. A decrease in the DC-Link voltage increases the current THD ratio of the DC/AC converter.

Moreover, the voltage drops in all phases (symmetrical voltage drops) do not affect the output current THD level. According to Figure 4.9, current THD is under 1.1%, and it is closed to the balance system result. quantity.

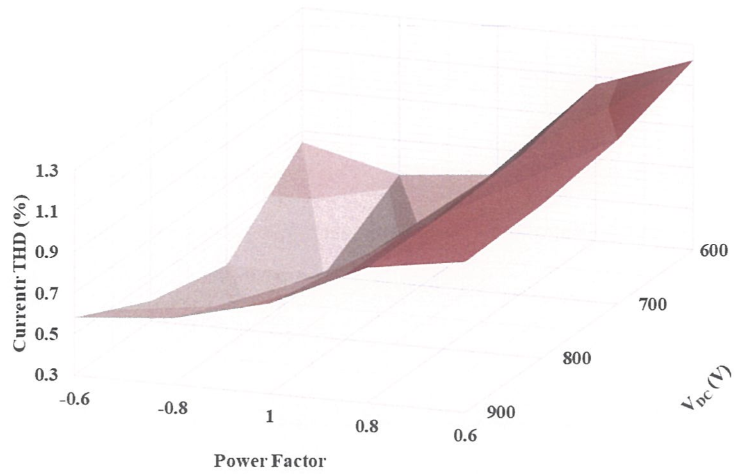

Figure 4.2: Current THD results with Electrolytic DC-Link capacitor at grid condition 1

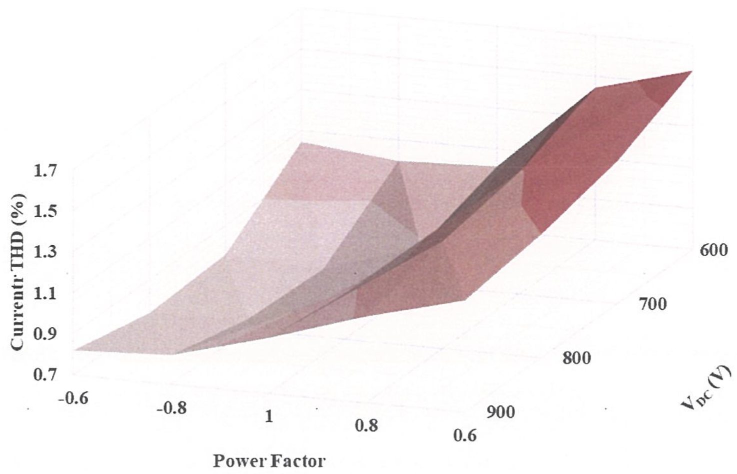

Figure 4.3: Current THD results with Electrolytic DC-Link capacitor at grid condition 2

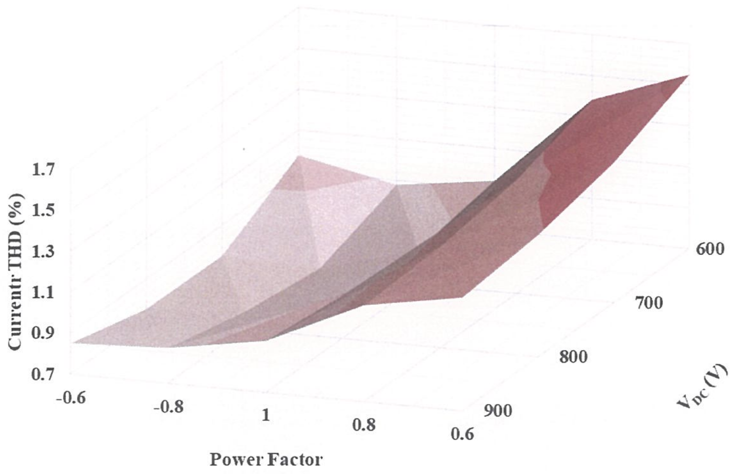

Figure 4.4: Current THD results with Electrolytic DC-Link capacitor at grid condition 3

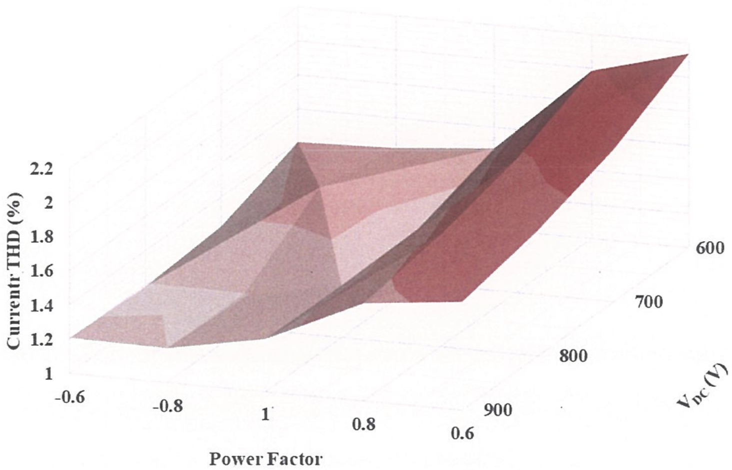

Figure 4.5: Current THD results with Electrolytic DC-Link capacitor at grid condition 4

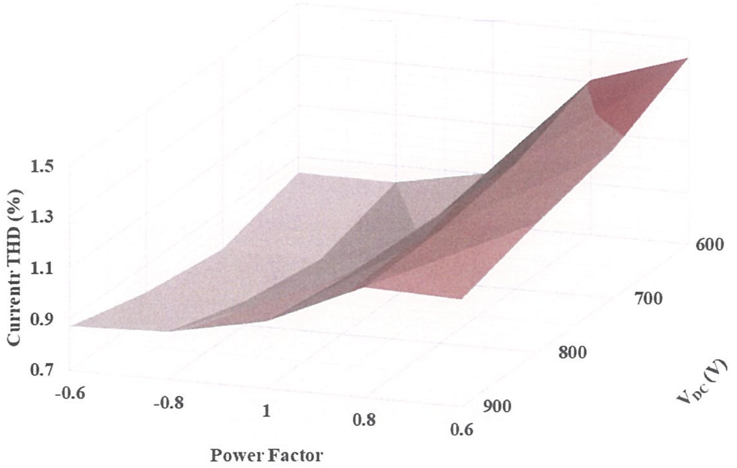

Figure 4.6: Current THD results with Electrolytic DC-Link capacitor at grid condition 5

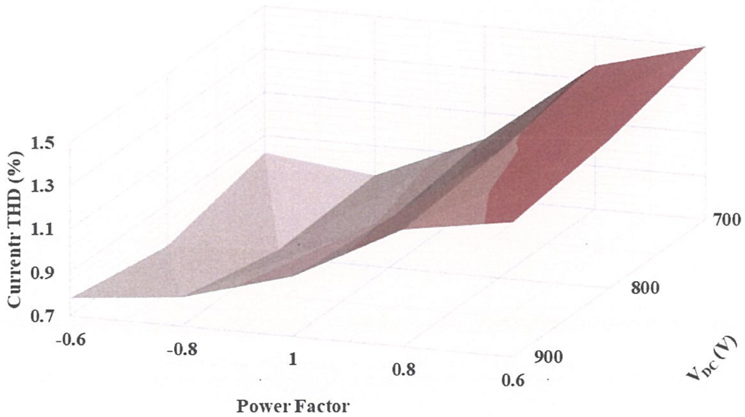

Figure 4.7: Current THD results with Electrolytic DC-Link capacitor at grid condition 6

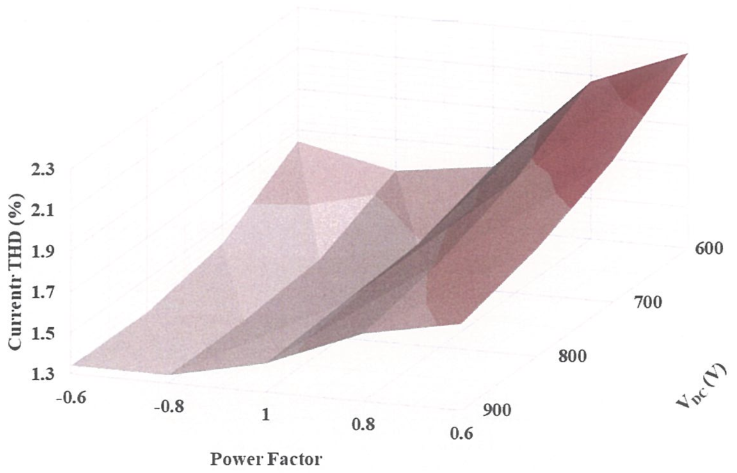

Figure 4.8: Current THD results with Electrolytic DC-Link capacitor at grid condition 7

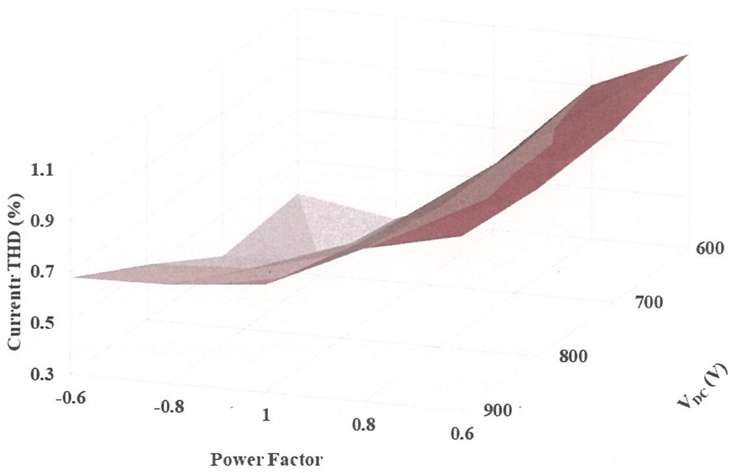

Figure 4.9: Current THD results with Electrolytic DC-Link capacitor at grid condition 8

Table 4.9: Output currents without unbalance controller at 900V

Power Factor	Grid Conditions	I_f	I_{3f}	I_{5f}	I_{7f}	I_{11f}	I_{13f}	$I_{f_{sw}}$	$I_{f_{2sw}}$
1	1	14.76333	7.17E-05	0.068273	0.048275	0.011088	0.005276	0.063243	0.007668
1	2	14.36279	0.087331	0.071895	0.055858	0.012584	0.006815	0.060077	0.009443
1	3	15.33288	0.094946	0.072841	0.04674	0.011246	0.006199	0.072837	0.008306
1	4	14.84432	0.157788	0.076992	0.053342	0.01227	0.007334	0.067379	0.009816
1	5	15.88177	0.098295	0.07009	0.046719	0.009581	0.006677	0.079339	0.00757
1	6	13.91521	0.084684	0.073672	0.053278	0.014318	0.007121	0.055792	0.011349
1	7	15.93677	0.197753	0.076009	0.045857	0.011189	0.006083	0.082822	0.007812
1	8	16.39258	1.61E-05	0.064997	0.039636	0.008474	0.005278	0.084495	0.006837
0.8	1	15.1522	1.61E-05	0.100534	0.076362	0.018092	0.006623	0.062775	0.009441
0.8	2	14.9785	0.09306	0.109991	0.087141	0.019769	0.009105	0.059393	0.010974
0.8	3	15.49744	0.097654	0.11151	0.075293	0.017948	0.007677	0.071529	0.008717
0.8	4	15.29848	0.177582	0.121083	0.085006	0.019071	0.008952	0.066009	0.010305
0.8	5	15.83268	0.097933	0.101839	0.07436	0.015541	0.008064	0.078274	0.007896
0.8	6	14.70697	0.092941	0.119407	0.087966	0.022501	0.00874	0.054574	0.011831
0.8	7	15.86734	0.201107	0.120054	0.07138	0.017031	0.007943	0.081434	0.008139
0.8	8	16.08745	1.83E-05	0.091975	0.064004	0.014133	0.005984	0.083721	0.007085
-0.8	1	13.8982	1.33E-05	0.041908	0.023597	0.005424	0.005415	0.065125	0.008666
-0.8	2	13.67234	0.078451	0.042201	0.027909	0.006507	0.006416	0.061768	0.010185
-0.8	3	14.34229	0.082748	0.044623	0.024951	0.006125	0.005627	0.073944	0.007978
-0.8	4	14.0929	0.139691	0.042608	0.028836	0.007005	0.006373	0.068653	0.009484
-0.8	5	14.71401	0.08622	0.045504	0.025825	0.005055	0.006014	0.080205	0.007345
-0.8	6	13.37229	0.075354	0.040775	0.026893	0.007805	0.006184	0.056962	0.011066
-0.8	7	14.81231	0.169934	0.046564	0.025935	0.006916	0.005138	0.08397	0.007567
-0.8	8	15.02519	2.09E-05	0.043823	0.021265	0.004296	0.005134	0.085124	0.006674
0.6	1	15.14879	1.73E-05	0.109797	0.084838	0.020017	0.007034	0.062544	0.009573
0.6	2	15.1169	0.094433	0.121435	0.096543	0.021789	0.009773	0.059165	0.011053
0.6	3	15.36009	0.098518	0.122393	0.083233	0.019805	0.008241	0.071279	0.008887
0.6	4	15.28293	0.176987	0.133369	0.09385	0.021044	0.009738	0.065762	0.010435
0.6	5	15.55859	0.097138	0.111464	0.082119	0.017257	0.008623	0.078017	0.008077
0.6	6	14.96812	0.095992	0.132286	0.097583	0.024794	0.009453	0.054323	0.011831
0.6	7	15.58237	0.200732	0.132452	0.078385	0.018669	0.008588	0.081242	0.008346
0.6	8	15.63685	1.65E-05	0.09961	0.07088	0.015757	0.006306	0.083457	0.007261
-0.6	1	13.89492	1.53E-05	0.032149	0.016393	0.003601	0.005507	0.065603	0.008629
-0.6	2	13.77933	0.079633	0.032134	0.019457	0.004399	0.006315	0.062284	0.010173
-0.6	3	14.23306	0.08305	0.037362	0.018689	0.004613	0.005745	0.074448	0.007933
-0.6	4	14.10278	0.142294	0.03736	0.020211	0.005238	0.006341	0.069233	0.009387
-0.6	5	14.41806	0.084582	0.03654	0.018951	0.003864	0.005968	0.080586	0.007282
-0.6	6	13.64287	0.079223	0.031659	0.019097	0.005472	0.006232	0.057516	0.011065
-0.6	7	14.58825	0.169924	0.042038	0.02089	0.005799	0.005277	0.0845	0.007548
-0.6	8	14.59034	1.92E-05	0.035815	0.015497	0.003304	0.005213	0.08542	0.006629

Table 4.10: Output currents without unbalance controller at 800V

Power Factor	Grid Conditions	I_f	I_{3f}	I_{5f}	I_{7f}	I_{11f}	I_{13f}	$I_{f_{sw}}$	$I_{f_{2sw}}$
1	1	14.41731	1.79E-05	0.059502	0.048724	0.013351	0.006122	0.043178	0.011361
1	2	14.02365	0.089702	0.062429	0.056094	0.014831	0.008151	0.040926	0.012426
1	3	14.96896	0.09773	0.066214	0.049379	0.013607	0.006433	0.049577	0.010847
1	4	14.49562	0.162615	0.069267	0.056191	0.014605	0.008097	0.045873	0.01209
1	5	15.50749	0.101579	0.064963	0.049203	0.011455	0.006769	0.055736	0.010216
1	6	13.58549	0.085967	0.0616	0.056071	0.017274	0.007816	0.037849	0.012728
1	7	15.55366	0.204124	0.070807	0.048594	0.01324	0.006215	0.057801	0.010312
1	8	16.00858	2.1E-05	0.060555	0.042047	0.010176	0.005005	0.062515	0.009347
0.8	1	15.03274	1.89E-05	0.099768	0.086658	0.022174	0.007115	0.042116	0.011743
0.8	2	14.85814	0.10056	0.109253	0.098608	0.024016	0.010247	0.039898	0.012714
0.8	3	15.36676	0.105639	0.114151	0.085269	0.021997	0.008156	0.048369	0.011244
0.8	4	15.16659	0.191839	0.124086	0.096032	0.023046	0.010298	0.044775	0.012446
0.8	5	15.70438	0.105788	0.104155	0.083906	0.018877	0.00856	0.054489	0.010616
0.8	6	14.58287	0.100587	0.118057	0.099774	0.027458	0.009608	0.037013	0.012902
0.8	7	15.72504	0.217634	0.125566	0.080632	0.020616	0.008463	0.056296	0.010712
0.8	8	16.74265	1.95E-05	0.097543	0.076295	0.018202	0.00596	0.060882	0.009839
-0.8	1	13.91713	2.6E-05	0.02729	0.019664	0.006121	0.005429	0.044119	0.0111
-0.8	2	13.68803	0.082558	0.025327	0.02342	0.00746	0.006545	0.041848	0.012281
-0.8	3	14.36542	0.087758	0.032707	0.021267	0.006737	0.005417	0.050628	0.010583
-0.8	4	14.11191	0.15082	0.03044	0.024937	0.007794	0.006313	0.04687	0.01191
-0.8	5	14.73195	0.091663	0.033791	0.022488	0.005435	0.00556	0.056884	0.009911
-0.8	6	13.39162	0.080763	0.022459	0.022052	0.008963	0.006518	0.038627	0.012649
-0.8	7	14.84042	0.181019	0.037328	0.023058	0.007355	0.00485	0.059045	0.010023
-0.8	8	15.04712	1.4E-05	0.034021	0.018559	0.004387	0.004595	0.063786	0.008999
0.6	1	15.13367	2.18E-05	0.111405	0.097552	0.024625	0.007575	0.041863	0.011724
0.6	2	15.09819	0.103643	0.123639	0.110764	0.026548	0.01096	0.039652	0.012667
0.6	3	15.34994	0.108121	0.127994	0.095493	0.024288	0.008831	0.048153	0.011305
0.6	4	15.25311	0.193847	0.139648	0.107415	0.025458	0.011178	0.04453	0.012439
0.6	5	15.53769	0.106396	0.116401	0.093942	0.020916	0.00925	0.05429	0.010764
0.6	6	14.96084	0.105489	0.134341	0.112189	0.030293	0.010312	0.036799	0.012856
0.6	7	15.57617	0.220291	0.141411	0.089643	0.022598	0.009266	0.056056	0.010815
0.6	8	15.61919	1.93E-05	0.103325	0.081556	0.019267	0.006255	0.060808	0.009977
-0.6	1	13.8419	2.75E-05	0.014674	0.010891	0.003189	0.005409	0.044578	0.011136
-0.6	2	13.72692	0.084546	0.01521	0.012933	0.004378	0.006182	0.042306	0.012276
-0.6	3	14.1811	0.088815	0.023282	0.013651	0.004091	0.005398	0.051174	0.010573
-0.6	4	14.0507	0.150912	0.023401	0.013929	0.005032	0.005964	0.047385	0.011882
-0.6	5	14.35627	0.089368	0.024538	0.013904	0.003135	0.005362	0.057474	0.009883
-0.6	6	13.59806	0.084745	0.010417	0.012751	0.005519	0.006234	0.038991	0.012634
-0.6	7	14.53762	0.182362	0.03161	0.016453	0.005216	0.004825	0.059659	0.009961
-0.6	8	14.52809	1.56E-05	0.023778	0.011425	0.002353	0.004651	0.064394	0.008912

Table 4.11: Output currents without unbalance controller at 700V

Power Factor	Grid Conditions	I_f	I_{3f}	I_{5f}	I_{7f}	I_{11f}	I_{13f}	$I_{f_{sw}}$	$I_{f_{2sw}}$
1	1	14.45659	2.72E-05	0.043392	0.051819	0.01693	0.007059	0.031547	0.011337
1	2	14.05498	0.095567	0.044765	0.059078	0.019082	0.009651	0.035669	0.011051
1	3	15.00119	0.102952	0.052885	0.052698	0.017024	0.007562	0.034314	0.011956
1	4	14.52893	0.173282	0.05436	0.059524	0.018154	0.009725	0.037652	0.011814
1	5	15.54289	0.10765	0.054767	0.052348	0.01452	0.007706	0.036061	0.011892
1	6	13.6156	0.093197	0.040021	0.059134	0.022113	0.009689	0.042044	0.01063
1	7	15.57815	0.215974	0.060276	0.051998	0.016388	0.007323	0.038893	0.012131
1	8	16.05168	1.86E-05	0.051835	0.044945	0.012833	0.005542	0.039777	0.011754
0.8	1	15.04829	1.53E-05	0.093849	0.101406	0.028284	0.008265	0.031725	0.011247
0.8	2	14.86945	0.111089	0.103657	0.114477	0.030924	0.01224	0.036511	0.010884
0.8	3	15.37086	0.116711	0.113877	0.099525	0.027733	0.009531	0.034193	0.012005
0.8	4	15.16594	0.211215	0.124113	0.111458	0.028876	0.012848	0.038276	0.011739
0.8	5	15.71777	0.116688	0.104158	0.097717	0.024128	0.009991	0.035325	0.012058
0.8	6	14.59643	0.111457	0.11102	0.1161	0.035147	0.011984	0.043405	0.010398
0.8	7	15.71766	0.240532	0.130531	0.093648	0.025763	0.00989	0.038439	0.012348
0.8	8	15.97809	2.22E-05	0.093757	0.084976	0.02207	0.006613	0.038662	0.012017
-0.8	1	13.94105	3.04E-05	0.010022	0.013144	0.00761	0.006006	0.03148	0.011418
-0.8	2	13.70816	0.088256	0.017211	0.015801	0.009406	0.007387	0.034931	0.011205
-0.8	3	14.3925	0.094868	0.014896	0.015571	0.008119	0.00589	0.034522	0.011932
-0.8	4	14.13414	0.165756	0.016989	0.018469	0.009474	0.007075	0.03719	0.011838
-0.8	5	14.75379	0.098513	0.017909	0.016864	0.006591	0.005821	0.036808	0.0118
-0.8	6	13.41472	0.087806	0.023629	0.014193	0.011311	0.007596	0.04082	0.010766
-0.8	7	14.87213	0.197432	0.020801	0.01861	0.008608	0.005226	0.039321	0.011921
-0.8	8	15.07359	2.82E-05	0.018368	0.013648	0.005225	0.004759	0.040805	0.011556
0.6	1	15.20456	3.04E-05	0.108814	0.115993	0.031498	0.008635	0.03178	0.011201
0.6	2	15.16353	0.116012	0.121719	0.130826	0.034263	0.013021	0.036721	0.010823
0.6	3	15.43027	0.120967	0.131843	0.113153	0.030734	0.010069	0.034186	0.011989
0.6	4	15.60253	0.064981	0.089671	0.084678	0.033775	0.018679	0.038394	0.011724
0.6	5	15.60402	0.118784	0.120152	0.111067	0.026761	0.01073	0.035173	0.012073
0.6	6	15.0412	0.118348	0.132208	0.132784	0.038814	0.012538	0.043753	0.010334
0.6	7	15.66466	0.246602	0.151291	0.105637	0.028341	0.010617	0.03835	0.012388
0.6	8	15.6907	1.95E-05	0.106065	0.096724	0.024588	0.006976	0.038442	0.0121
-0.6	1	15.3259	2.68E-05	0.01816	0.003303	0.00431	0.005594	0.031488	0.011402
-0.6	2	15.14108	0.099615	0.033899	0.00535	0.006182	0.006509	0.03469	0.011227
-0.6	3	15.74368	0.106004	0.018245	0.005485	0.004842	0.005302	0.034616	0.011897
-0.6	4	15.5367	0.181753	0.029818	0.006288	0.00633	0.006085	0.037034	0.011827
-0.6	5	14.3455	0.096362	0.011171	0.006793	0.003434	0.005209	0.037116	0.011758
-0.6	6	13.59471	0.092178	0.043172	0.007258	0.006859	0.006881	0.040309	0.010798
-0.6	7	14.53739	0.199337	0.021895	0.010076	0.005332	0.004726	0.03952	0.011891
-0.6	8	14.51944	2.34E-05	0.005441	0.00568	0.002009	0.004628	0.041269	0.011497

Table 4.12: Output currents without unbalance controller at 600V

Power Factor	Grid Conditions	I_f	I_{3f}	I_{5f}	I_{7f}	I_{11f}	I_{13f}	$I_{f_{sw}}$	$I_{f_{2sw}}$
1	1	14.47719	1.35E-05	0.024163	0.055056	0.022814	0.009604	0.050805	0.006665
1	2	14.06392	0.110542	0.030769	0.061781	0.026004	0.013198	0.061594	0.005964
1	3	15.01265	0.115732	0.031098	0.056262	0.022925	0.010305	0.05153	0.008554
1	4	14.53652	0.19515	0.034781	0.062577	0.024326	0.013375	0.063048	0.007758
1	5	15.5552	0.118998	0.037281	0.055775	0.019813	0.009885	0.043049	0.009496
1	6	14.90738	2.571673	2.24431	1.567724	0.455754	0.249354	0.073021	0.005281
1	7	15.57908	0.237423	0.040658	0.055708	0.021836	0.0101	0.053834	0.010163
1	8	16.07433	2.9E-05	0.034897	0.048701	0.017272	0.006936	0.035148	0.010362
0.8	1	15.08425	3.01E-05	0.07859	0.122241	0.037982	0.010909	0.052775	0.006293
0.8	2	14.90046	0.125095	0.089981	0.136811	0.041837	0.016265	0.063577	0.005653
0.8	3	15.42204	0.131951	0.106957	0.119634	0.037116	0.012936	0.053488	0.008211
0.8	4	15.1806	0.236577	0.11827	0.13288	0.038359	0.017441	0.065121	0.007418
0.8	5	15.75482	0.131092	0.099264	0.117267	0.03263	0.012774	0.044688	0.009224
0.8	6	16.16922	4.076295	3.425539	2.119348	0.451546	0.352156	0.0742	0.005057
0.8	7	15.77715	0.271035	0.131609	0.111945	0.034091	0.013666	0.055687	0.009898
0.8	8	16.02138	2.5E-05	0.087624	0.102971	0.029485	0.008125	0.036277	0.010147
-0.8	1	13.95885	2.18E-05	0.052192	0.004746	0.010579	0.008087	0.049024	0.00701
-0.8	2	13.72141	0.096467	0.072763	0.007386	0.012938	0.010136	0.059622	0.006252
-0.8	3	14.41125	0.104741	0.046107	0.007465	0.011258	0.007675	0.049732	0.008859
-0.8	4	14.1464	0.186602	0.060167	0.008873	0.013087	0.009529	0.061168	0.008061
-0.8	5	14.76745	0.107883	0.036356	0.007573	0.00925	0.007227	0.041538	0.009741
-0.8	6	14.22225	1.471922	1.307168	1.046239	0.419487	0.232003	0.071412	0.005527
-0.8	7	14.89363	0.219319	0.041395	0.011875	0.011486	0.006829	0.052092	0.01032
-0.8	8	15.0923	1.88E-05	0.021728	0.006019	0.007265	0.005724	0.034212	0.010551
0.6	1	15.16563	2.11E-05	0.09724	0.141587	0.042151	0.011164	0.053249	0.006204
0.6	2	15.11266	0.134428	0.117951	0.151229	0.051755	0.011416	0.064043	0.00558
0.6	3	15.40702	0.137016	0.12986	0.1377	0.04096	0.013486	0.053946	0.008121
0.6	4	15.27187	0.243967	0.143718	0.152973	0.042305	0.018339	0.065635	0.007334
0.6	5	15.56426	0.134128	0.118225	0.134844	0.036006	0.013459	0.045056	0.009148
0.6	6	17.0508	4.464753	3.742553	2.243086	0.469252	0.38432	0.074423	0.004998
0.6	7	15.65494	0.279507	0.158344	0.127833	0.037402	0.014508	0.056103	0.009832
0.6	8	15.65972	1.59E-05	0.103133	0.118471	0.032855	0.008413	0.036554	0.010086
-0.6	1	13.88516	1.5E-05	0.071531	0.018263	0.005969	0.007364	0.04826	0.007148
-0.6	2	13.76607	0.099684	0.097439	0.020895	0.008444	0.008756	0.05877	0.006375
-0.6	3	14.23135	0.107434	0.069336	0.016044	0.006594	0.006669	0.048951	0.008963
-0.6	4	14.09327	0.179472	0.086223	0.018033	0.008692	0.007872	0.060369	0.008176
-0.6	5	14.39731	0.105789	0.055811	0.013319	0.005627	0.006085	0.040874	0.009798
-0.6	6	14.16395	1.087472	0.955285	0.829187	0.374037	0.223228	0.070573	0.005624
-0.6	7	14.59733	0.223302	0.067952	0.013719	0.007154	0.005599	0.051319	0.010367
-0.6	8	14.57636	2.36E-05	0.035169	0.010915	0.003515	0.00521	0.033822	0.010586

Table 4.13: Current THD with electrolytic capacitor at grid condition 1

DC-Link Voltage	Power Factor				
	-0.6	-0.8	1	0.8	0.6
900	0.581	0.622	0.74	0.959	1.033
800	0.399	0.445	0.646	0.952	1.046
700	0.31	0.306	0.552	0.973	1.1
600	0.647	0.532	0.578	1.062	1.224

Table 4.14: Current THD with electrolytic capacitor at grid condition 2

DC-Link Voltage	Power Factor				
	-0.6	-0.8	1	0.8	0.6
900	0.819	0.841	0.97	1.12	1.242
800	0.739	0.751	0.923	1.224	1.3
700	0.759	0.732	0.889	1.295	1.394
600	1.046	0.998	1.016	1.445	1.573

Table 4.15: Current THD with electrolytic capacitor at grid condition 3

DC-Link Voltage	Power Factor				
	-0.6	-0.8	1	0.8	0.6
900	0.85	0.871	0.951	1.17	1.252
800	0.754	0.782	0.908	1.193	1.294
700	0.75	0.734	0.868	1.254	1.383
600	0.978	0.878	0.942	1.382	1.549

Table 4.16: Current THD with electrolytic capacitor at grid condition 4

DC-Link Voltage	Power Factor				
	-0.6	-0.8	1	0.8	0.6
900	1.207	1.2	1.307	1.57	1.633
800	1.19	1.194	1.305	1.654	1.736
700	1.228	1.51	1.32	1.781	1.893
600	1.406	1.424	1.476	1.985	2.139

Table 4.17: Current THD with electrolytic capacitor at grid condition 5

DC-Link Voltage	Power Factor				
	-0.6	-0.8	1	0.8	0.6
900	0.871	0.885	0.961	1.13	1.118
800	0.793	0.793	0.917	1.138	1.204
700	0.751	0.745	0.881	1.188	1.278
600	0.839	0.836	0.909	1.306	1.428

Table 4.18: Current THD with electrolytic capacitor at grid condition 6

DC-Link Voltage	Power Factor				
	-0.6	-0.8	1	0.8	0.6
900	0.781	0.832	0.976	1.24	1.321
800	0.707	0.735	0.92	1.282	1.384
700	0.82	0.763	0.979	1.364	1.5
600	14.06	18.626	28.73	39.19	41.22

Table 4.19: Current THD with electrolytic capacitor at grid condition 7

DC-Link Voltage	Power Factor				
	-0.6	-0.8	1	0.8	0.6
900	1.34	1.337	1.439	1.63	1.722
800	1.335	1.34	1.465	1.714	1.825
700	1.41	1.375	1.494	1.852	1.99
600	1.646	1.546	1.61	2.07	2.253

Table 4.20: Current THD with electrolytic capacitor at grid condition 8

DC-Link Voltage	Power Factor				
	-0.6	-0.8	1	0.8	0.6
900	0.677	0.684	0.72	0.895	0.98
800	0.516	0.53	0.631	0.848	0.954
700	0.338	0.354	0.525	0.855	0.974
600	0.373	0.309	0.464	0.903	1.06

4.1.2 Film DC-Link Capacitor

The electrolytic capacitor block model is modified with the film capacitor DC-Link block model in the simulation to examine the results. Same power factor and DC-Link voltage variations are considered in this case.The output grid currents of DC/AC converter with Film DC-Link capacitor block are given in Table 4.21 - Table 4.24 with respect to the DC-Link voltage. Furthermore, the DC/AC converter output current THDs are given in Table 4.25 - Table 4.32. The DC/AC converter output current THDs also given in Figure 4.10 - Figure 4.17 in 3D form to visualize the structure.

The decrease in the capacitance of the DC-Link with the changing capacitor type, the output current THDs become worse than an electrolytic DC-Link capacitor. Under unity power factor operation of the inverter, system stability is performed by film capacitors. Furthermore, almost all current THD results are under the IEEE 519-2014 THD limit, at unity power factor operation of the DC/AC converter. However, the output current THD goes up to 10% with the change of power factor even though the converter works in the grid condition 1.

The main problem with the film capacitor is the different power factor operations. Especially, the lagging power factor operation increases the output of current THD with no dependence on the grid condition. Seventy-one conditions out of a hundred thirty-nine conditions, the current THD is worse than or at the limit of the IEEE 519-2014 THD limit.

Furthermore, there is an inverse proportion between a DC-Link voltage and an output current THD ratio. The decrease in the DC-Link voltage rises the output current THD. There is also a nonlinear modulation region problem exists under the grid condition 6 at 600V DC-Link voltage. DC/AC converter enters over-modulation because of a 10% increase on two phases of the grid voltages. Therefore this condition does not exist in Figure 4.15.

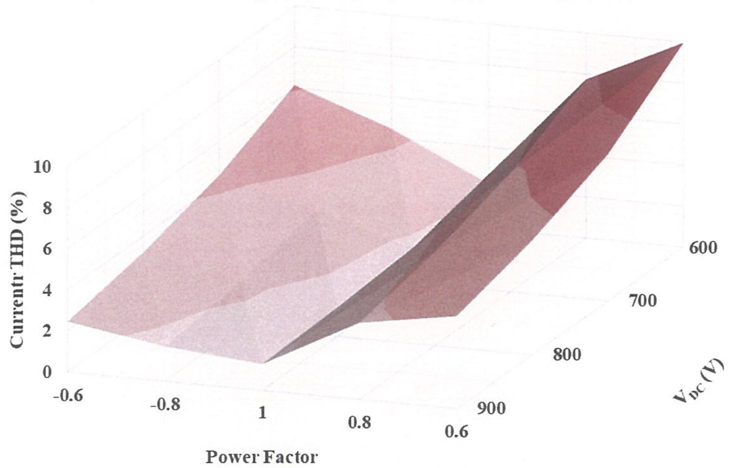

Figure 4.10: Current THD results with Film DC-Link capacitor at grid condition 1

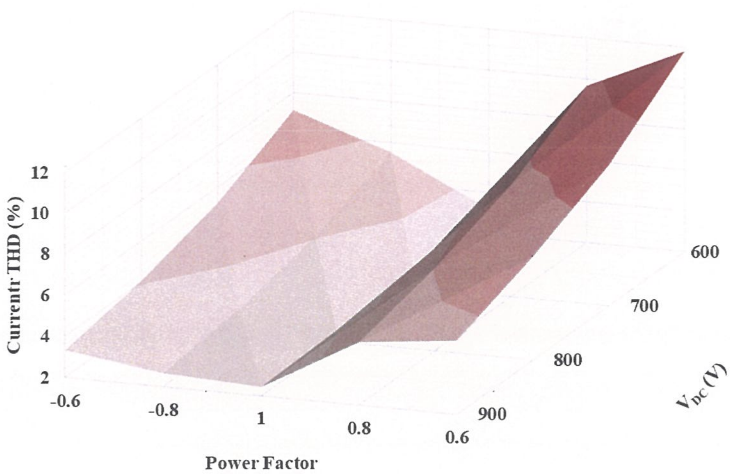

Figure 4.11: Current THD results with Film DC-Link capacitor at grid condition 2

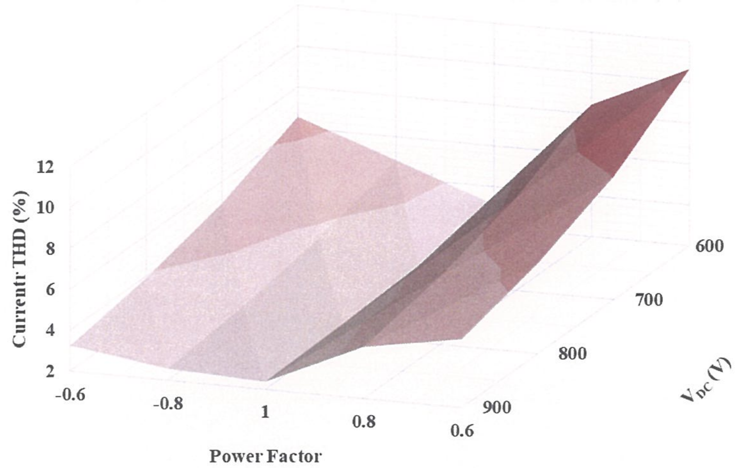

Figure 4.12: Current THD results with Film DC-Link capacitor at grid condition 3

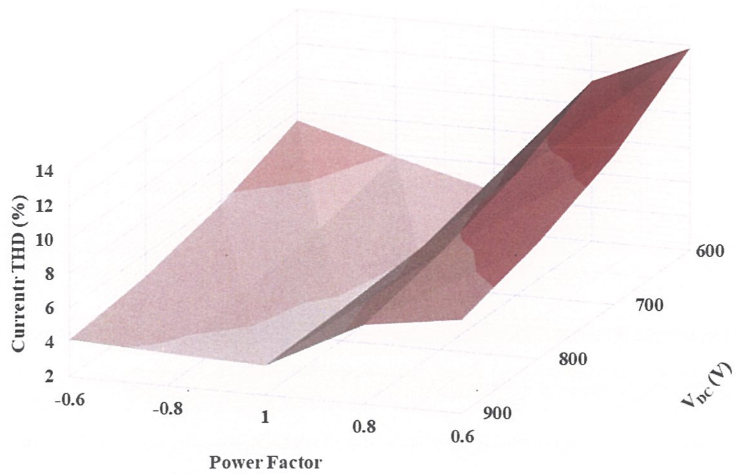

Figure 4.13: Current THD results with Film DC-Link capacitor at grid condition 4

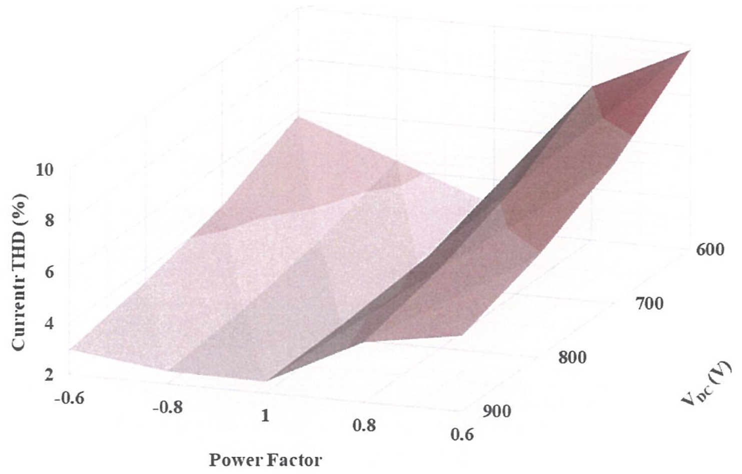

Figure 4.14: Current THD results with Film DC-Link capacitor at grid condition 5

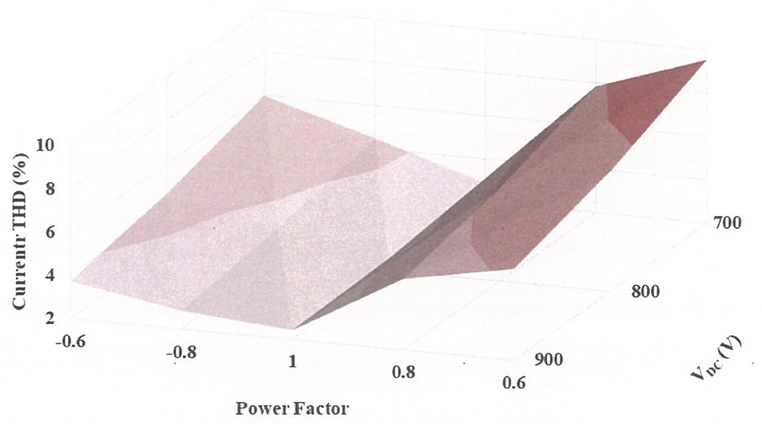

Figure 4.15: Current THD results with Film DC-Link capacitor at grid condition 6

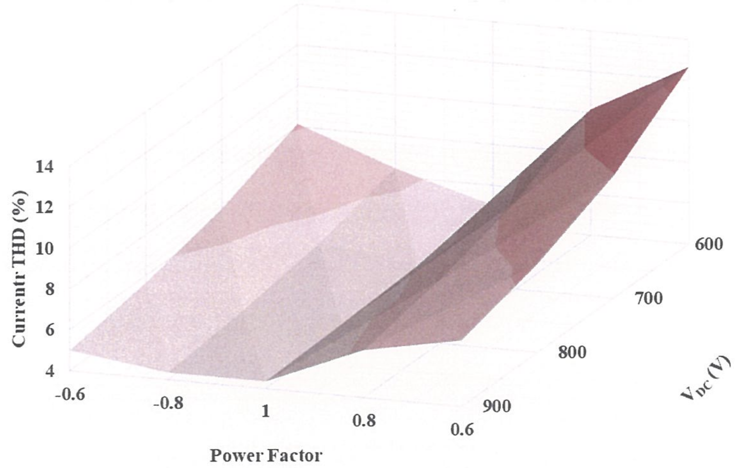

Figure 4.16: Current THD results with Film DC-Link capacitor at grid condition 7

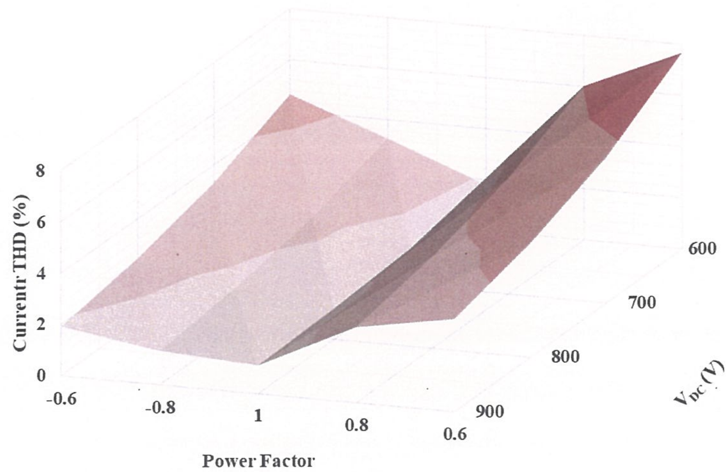

Figure 4.17: Current THD results with Film DC-Link capacitor at grid condition 8

Table 4.21: Output currents without unbalance controller at 900V

Power Factor	Grid Conditions	I_f	I_{3f}	I_{5f}	I_{7f}	I_{11f}	I_{13f}	$I_{f_{sw}}$	$I_{f_{2sw}}$
1	1	14.46293	3.12E-05	0.141889	0.088234	0.026183	0.008628	0.064591	0.008986
1	2	14.13403	0.274079	0.160734	0.100159	0.029748	0.011113	0.061217	0.010482
1	3	15.1003	0.307434	0.142193	0.092082	0.026558	0.010398	0.073479	0.008279
1	4	14.63126	0.513891	0.164059	0.103262	0.026868	0.012554	0.067818	0.009785
1	5	15.66847	0.323407	0.149278	0.087751	0.025096	0.009087	0.079988	0.007566
1	6	13.69624	0.260215	0.154935	0.104434	0.031572	0.012473	0.056351	0.011323
1	7	15.79072	0.654141	0.135729	0.095339	0.026091	0.01115	0.083586	0.007785
1	8	16.05999	1.66E-05	0.129097	0.07646	0.02167	0.007057	0.085133	0.006819
0.8	1	15.07347	6.29E-05	0.419377	0.357253	0.079454	0.011468	0.066181	0.009322
0.8	2	14.99599	0.389293	0.498379	0.402488	0.086522	0.01951	0.062967	0.010922
0.8	3	15.5002	0.411997	0.480904	0.346476	0.074264	0.019846	0.074801	0.008602
0.8	4	15.39689	0.743374	0.560955	0.387101	0.073077	0.02674	0.069402	0.010238
0.8	5	15.87827	0.409398	0.42481	0.332478	0.069759	0.01604	0.081787	0.007715
0.8	6	14.68853	0.391985	0.559561	0.417678	0.091425	0.024109	0.057815	0.011748
0.8	7	15.96148	0.85331	0.529464	0.320855	0.064826	0.025223	0.08443	0.008014
0.8	8	16.00725	2.05E-05	0.351272	0.291165	0.063804	0.008803	0.087434	0.006923
-0.8	1	13.97112	4.81E-05	0.164364	0.146516	0.041018	0.007435	0.064173	0.008738
-0.8	2	13.8418	0.261751	0.219427	0.162325	0.043435	0.012153	0.060925	0.010196
-0.8	3	14.5632	0.288449	0.181154	0.139364	0.03982	0.010245	0.07309	0.008026
-0.8	4	14.26558	0.487796	0.223639	0.154254	0.040233	0.011741	0.06783	0.009476
-0.8	5	14.93088	0.294424	0.175703	0.131673	0.035843	0.010093	0.079227	0.00746
-0.8	6	13.57797	0.259722	0.224303	0.170602	0.047705	0.012251	0.056352	0.01109
-0.8	7	15.19591	0.609291	0.209316	0.124299	0.034881	0.010957	0.083467	0.007739
-0.8	8	15.10937	3.02E-05	0.128093	0.117975	0.033671	0.005785	0.083916	0.006779
0.6	1	15.17384	7.18E-05	0.506503	0.440158	0.095989	0.01155	0.066919	0.009388
0.6	2	15.26653	0.394526	0.601256	0.494989	0.103734	0.021359	0.063844	0.011009
0.6	3	15.50423	0.412457	0.587516	0.423974	0.08857	0.021879	0.075425	0.008734
0.6	4	15.57824	0.786607	0.683244	0.473525	0.088237	0.030366	0.070521	0.010421
0.6	5	15.73088	0.403512	0.50674	0.406812	0.083382	0.017325	0.082638	0.007906
0.6	6	15.07484	0.404354	0.688713	0.513763	0.109201	0.026709	0.058682	0.011751
0.6	7	15.85545	0.850605	0.654554	0.389792	0.076153	0.02898	0.084929	0.008199
0.6	8	15.66714	7.14E-05	0.420229	0.356915	0.077064	0.008559	0.088178	0.007057
-0.6	1	13.8946	4.53E-05	0.240872	0.221863	0.059154	0.008966	0.064275	0.008715
-0.6	2	13.94722	0.286659	0.317529	0.247395	0.062896	0.016643	0.061186	0.010195
-0.6	3	14.38337	0.311193	0.270737	0.211862	0.05744	0.012475	0.073151	0.007995
-0.6	4	14.2106	0.479822	0.311782	0.234733	0.05676	0.01756	0.06811	0.009391
-0.6	5	14.61496	0.309525	0.256056	0.201655	0.051415	0.013827	0.079131	0.007448
-0.6	6	13.78915	0.291392	0.335207	0.258461	0.069499	0.015	0.056795	0.011131
-0.6	7	14.897	0.649364	0.306182	0.187607	0.04986	0.01335	0.083586	0.0078
-0.6	8	14.59079	5.55E-05	0.187494	0.179243	0.048178	0.006868	0.083627	0.006764

Table 4.22: Output currents without unbalance controller at 800V

Power Factor	Grid Conditions	I_f	I_{3f}	I_{5f}	I_{7f}	I_{11f}	I_{13f}	$I_{f_{sw}}$	$I_{f_{2sw}}$
1	1	14.43875	5.01E-05	0.16258	0.108681	0.035037	0.013227	0.043601	0.011345
1	2	14.1196	0.280597	0.183272	0.12252	0.039653	0.016715	0.041319	0.012419
1	3	15.10472	0.313845	0.164609	0.113067	0.035969	0.015574	0.050088	0.01083
1	4	14.62102	0.529414	0.187594	0.126169	0.03644	0.018646	0.046119	0.012066
1	5	15.65742	0.33196	0.172023	0.107704	0.033974	0.014025	0.056409	0.010198
1	6	13.69556	0.262667	0.17705	0.127929	0.042012	0.018183	0.038183	0.012709
1	7	15.8317	0.671101	0.158903	0.117095	0.035618	0.016334	0.058447	0.010281
1	8	16.03351	4.76E-05	0.149236	0.094709	0.02945	0.011001	0.063182	0.009327
0.8	1	15.06346	4.25E-05	0.507466	0.448116	0.100686	0.017347	0.044738	0.01167
0.8	2	14.99146	0.427673	0.605472	0.503669	0.110404	0.027645	0.042066	0.012659
0.8	3	15.47438	0.451875	0.587326	0.433947	0.094181	0.027757	0.051172	0.011181
0.8	4	15.37937	0.811958	0.685465	0.48408	0.094676	0.036379	0.047634	0.012384
0.8	5	15.87956	0.448245	0.517605	0.415348	0.089449	0.02283	0.057883	0.01057
0.8	6	14.66516	0.430953	0.681735	0.523998	0.115504	0.03351	0.038131	0.012814
0.8	7	15.91947	0.935672	0.650626	0.401736	0.082299	0.03432	0.058923	0.010629
0.8	8	15.99611	5.04E-05	0.425287	0.364848	0.081197	0.013339	0.065003	0.009629
-0.8	1	13.93361	2.57E-05	0.230166	0.193469	0.053069	0.011438	0.044058	0.011167
-0.8	2	13.81902	0.276796	0.300547	0.215016	0.056418	0.017576	0.042363	0.012314
-0.8	3	14.55247	0.306331	0.246626	0.185313	0.05186	0.015147	0.050389	0.010609
-0.8	4	14.26858	0.5108	0.30073	0.20588	0.052505	0.016885	0.046957	0.011896
-0.8	5	14.90775	0.310026	0.241112	0.175131	0.046508	0.014831	0.056309	0.009923
-0.8	6	13.56433	0.277909	0.309493	0.226026	0.06219	0.017847	0.03971	0.012703
-0.8	7	15.21816	0.648797	0.273437	0.166966	0.046006	0.015818	0.059077	0.010027
-0.8	8	15.0668	3.87E-05	0.179795	0.156036	0.043647	0.009356	0.062833	0.009071
0.6	1	15.13378	4.81E-05	0.619285	0.555273	0.121107	0.01783	0.045418	0.011622
0.6	2	15.23396	0.44004	0.741955	0.623088	0.131752	0.030774	0.042745	0.012623
0.6	3	15.44782	0.45831	0.724995	0.533845	0.112272	0.030459	0.05183	0.01123
0.6	4	15.5324	0.870523	0.843497	0.595418	0.11413	0.040871	0.048635	0.012422
0.6	5	15.69836	0.44494	0.624265	0.510903	0.106245	0.024896	0.058845	0.010742
0.6	6	15.02608	0.451702	0.848745	0.648344	0.138748	0.037259	0.038537	0.012756
0.6	7	15.78147	0.943858	0.812877	0.490683	0.095405	0.039298	0.059416	0.010738
0.6	8	15.61987	4.82E-05	0.513362	0.449433	0.097369	0.013181	0.065906	0.009791
-0.6	1	13.84125	5.38E-05	0.327599	0.286024	0.07568	0.012894	0.04464	0.011202
-0.6	2	13.91075	0.309354	0.423753	0.319734	0.080913	0.022957	0.043238	0.012306
-0.6	3	14.35272	0.337489	0.361286	0.274777	0.074004	0.01773	0.050883	0.010621
-0.6	4	14.19147	0.50156	0.412055	0.305437	0.073228	0.023339	0.047813	0.011892
-0.6	5	14.57418	0.332237	0.342352	0.261307	0.065909	0.019077	0.056678	0.009888
-0.6	6	13.759	0.31829	0.446911	0.334326	0.089726	0.021493	0.040688	0.012695
-0.6	7	14.89345	0.705624	0.399684	0.245324	0.064771	0.018524	0.059663	0.010045
-0.6	8	14.52813	1.28E-05	0.256248	0.231346	0.061677	0.010268	0.063036	0.008989

Table 4.23: Output currents without unbalance controller at 700V

Power Factor	Grid Conditions	I_f	I_{3f}	I_{5f}	I_{7f}	I_{11f}	I_{13f}	$I_{f_{sw}}$	$I_{f_{2sw}}$
1	1	14.39085	4.93E-05	0.192669	0.139128	0.0475	0.019525	0.031377	0.011322
1	2	14.07923	0.290111	0.215937	0.155464	0.053712	0.02446	0.035415	0.011043
1	3	15.08334	0.315767	0.19703	0.144272	0.04914	0.022781	0.034248	0.01196
1	4	14.61855	0.54096	0.22164	0.159929	0.049889	0.027039	0.03705	0.01182
1	5	15.6159	0.340502	0.204762	0.137444	0.046428	0.021084	0.036505	0.011895
1	6	13.6712	0.270534	0.209936	0.162207	0.056938	0.026148	0.041489	0.010607
1	7	15.84631	0.678812	0.192614	0.149304	0.048953	0.023745	0.038948	0.012151
1	8	15.97986	5.57E-05	0.178825	0.12169	0.040399	0.016693	0.040209	0.011745
0.8	1	15.04929	5.12E-05	0.633775	0.583426	0.131514	0.026467	0.029437	0.011121
0.8	2	14.97505	0.479642	0.758295	0.653111	0.145406	0.04003	0.032371	0.010738
0.8	3	15.4409	0.503953	0.741096	0.563961	0.122534	0.039687	0.032761	0.011848
0.8	4	15.34692	0.904622	0.863902	0.627397	0.126771	0.050712	0.03444	0.011601
0.8	5	15.86828	0.499343	0.651219	0.538102	0.117957	0.033088	0.036186	0.011946
0.8	6	14.63574	0.483111	0.857858	0.681729	0.150739	0.047866	0.037871	0.010257
0.8	7	15.86439	1.041696	0.82744	0.521991	0.10715	0.048179	0.03716	0.01211
0.8	8	15.97992	8.35E-05	0.5325	0.474205	0.106174	0.02067	0.041216	0.01193
-0.8	1	13.91301	7.51E-05	0.330275	0.261626	0.070766	0.017682	0.034242	0.011507
-0.8	2	13.81279	0.298017	0.421575	0.291729	0.075726	0.026125	0.038375	0.011298
-0.8	3	14.55825	0.330252	0.347708	0.252531	0.069891	0.022453	0.036797	0.012035
-0.8	4	14.28706	0.539945	0.414501	0.281391	0.07059	0.024612	0.04016	0.011965
-0.8	5	14.90122	0.329761	0.337758	0.238271	0.062517	0.022102	0.038228	0.01188
-0.8	6	13.56457	0.303952	0.436366	0.307339	0.083357	0.026302	0.044583	0.010854
-0.8	7	15.2584	0.700123	0.374656	0.230199	0.062737	0.022707	0.041606	0.01211
-0.8	8	15.04243	9.57E-05	0.257446	0.2117	0.058369	0.014609	0.041303	0.011608
0.6	1	15.14516	0.000134	0.783971	0.728802	0.157543	0.02869	0.029296	0.011037
0.6	2	15.24195	0.507166	0.951054	0.814773	0.172968	0.046132	0.031679	0.010649
0.6	3	15.44415	0.524129	0.927164	0.699062	0.148919	0.04427	0.032733	0.011795
0.6	4	15.52899	0.992141	1.077531	0.777643	0.153168	0.057479	0.034042	0.011533
0.6	5	15.71619	0.507902	0.800248	0.666827	0.139566	0.037009	0.036584	0.011911
0.6	6	15.02274	0.520459	1.084054	0.85065	0.183864	0.054661	0.036926	0.010161
0.6	7	15.75971	1.076317	1.047754	0.642257	0.123398	0.055555	0.037038	0.012061
0.6	8	15.63385	0.000107	0.650271	0.58833	0.126747	0.021397	0.042017	0.011956
-0.6	1	13.83424	0.000112	0.456819	0.377959	0.09993	0.019975	0.0356	0.011521
-0.6	2	13.9185	0.342171	0.579261	0.423457	0.10751	0.033601	0.039633	0.011358
-0.6	3	14.36873	0.374265	0.492802	0.3655	0.098713	0.026185	0.038028	0.012069
-0.6	4	14.21506	0.533329	0.557762	0.40759	0.09762	0.033378	0.041552	0.01203
-0.6	5	14.58382	0.363274	0.467909	0.346921	0.08766	0.027635	0.039248	0.011871
-0.6	6	13.76764	0.357372	0.610114	0.443969	0.119434	0.031759	0.045821	0.010928
-0.6	7	14.9389	0.782915	0.531893	0.329733	0.087447	0.026244	0.042912	0.012146
-0.6	8	14.51901	5.53E-05	0.357573	0.30643	0.081502	0.015644	0.04216	0.011543

Table 4.24: Output currents without unbalance controller at 600V

Power Factor	Grid Conditions	I_f	I_{3f}	I_{5f}	I_{7f}	I_{11f}	I_{13f}	$I_{f_{sw}}$	$I_{f_{2sw}}$
1	1	14.47806	8.82E-05	0.244954	0.187805	0.066837	0.029328	0.050236	0.006649
1	2	14.16888	0.304578	0.272868	0.207801	0.075146	0.036713	0.060938	0.005928
1	3	15.20121	0.32792	0.251073	0.194064	0.069679	0.033855	0.050838	0.008539
1	4	14.75012	0.555228	0.279668	0.213386	0.070902	0.040219	0.062325	0.007725
1	5	15.71692	0.356523	0.258119	0.185173	0.065735	0.03185	0.042486	0.009484
1	6	13.97148	1.575814	2.005135	1.159167	0.268714	0.169924	0.072021	0.005342
1	7	16.00583	0.684959	0.247868	0.200594	0.069725	0.035032	0.052977	0.010132
1	8	16.07642	5.32E-05	0.227158	0.165521	0.057464	0.025241	0.034703	0.010348
0.8	1	15.08482	0.000115	0.830347	0.798148	0.179175	0.042494	0.045827	0.006149
0.8	2	14.99263	0.554295	0.994452	0.888786	0.199964	0.061297	0.056168	0.005496
0.8	3	15.47659	0.578219	0.978657	0.769871	0.169673	0.059577	0.046159	0.008073
0.8	4	15.34723	1.044433	1.135654	0.852785	0.177765	0.074664	0.057353	0.007298
0.8	5	15.8998	0.573899	0.855715	0.731384	0.16248	0.050056	0.038065	0.009081
0.8	6	15.56234	2.39099	3.464664	1.643685	0.277563	0.133805	0.066508	0.005008
0.8	7	15.91999	1.191072	1.100067	0.712882	0.145334	0.070672	0.047899	0.009733
0.8	8	16.02273	8.59E-06	0.697729	0.648093	0.144625	0.033046	0.031222	0.009989
-0.8	1	13.93438	0.000101	0.488782	0.366588	0.097704	0.02789	0.053329	0.007077
-0.8	2	13.84794	0.332483	0.60888	0.409657	0.105536	0.03989	0.063978	0.006317
-0.8	3	14.60406	0.366746	0.504984	0.356508	0.097565	0.034129	0.054205	0.008932
-0.8	4	14.33909	0.584519	0.589803	0.398299	0.097977	0.037923	0.065729	0.008099
-0.8	5	14.93976	0.359457	0.488571	0.334899	0.087558	0.033961	0.045982	0.009846
-0.8	6	13.78606	0.894985	0.918528	1.157418	0.310221	0.215595	0.075154	0.005648
-0.8	7	15.33908	0.775647	0.528147	0.329256	0.088966	0.033629	0.056709	0.010466
-0.8	8	15.0651	1.76E-05	0.381545	0.296652	0.080985	0.023203	0.038417	0.010652
0.6	1	15.16524	0.000135	1.045211	1.008299	0.213586	0.050162	0.044456	0.006018
0.6	2	15.24188	0.607688	1.287944	1.121312	0.23739	0.074575	0.054713	0.005387
0.6	3	15.44906	0.62234	1.245165	0.964004	0.207174	0.069281	0.044731	0.007951
0.6	4	15.51799	1.183772	1.438119	1.062942	0.219229	0.085837	0.055809	0.00719
0.6	5	15.73026	0.604514	1.082069	0.91546	0.191338	0.058774	0.036789	0.008981
0.6	6	16.04926	2.537043	3.797568	1.821563	0.401687	0.166377	0.064585	0.004879
0.6	7	15.74381	1.271887	1.416495	0.885327	0.177808	0.083413	0.04634	0.009624
0.6	8	15.65984	8.59E-05	0.86471	0.811901	0.171787	0.036993	0.030557	0.009887
-0.6	1	13.84764	0.0001	0.65724	0.516718	0.137061	0.032317	0.054437	0.007248
-0.6	2	13.94594	0.393217	0.815535	0.579994	0.149288	0.051438	0.065001	0.006477
-0.6	3	14.39988	0.429329	0.693481	0.503348	0.137155	0.040234	0.055435	0.009073
-0.6	4	14.24653	0.611229	0.777718	0.562963	0.134907	0.050641	0.066927	0.008238
-0.6	5	14.61473	0.409435	0.65983	0.475592	0.121792	0.042303	0.047315	0.009947
-0.6	6	13.98172	0.662809	1.065309	1.166526	0.304823	0.21972	0.076125	0.005769
-0.6	7	14.99618	0.896068	0.728193	0.459734	0.123238	0.038609	0.058074	0.010539
-0.6	8	14.5327	3.92E-05	0.516106	0.419091	0.112041	0.025403	0.040013	0.010729

Table 4.25: Current THD with film capacitor at grid condition 1

DC-Link Voltage	**Power Factor**				
	-0.6	**-0.8**	**1**	**0.8**	**0.6**
900	2.451	1.682	1.269	3.726	4.496
800	3.214	2.224	1.423	4.56	5.569
700	4.362	3.089	1.711	5.801	7.155
600	6.14	4.465	2.223	7.744	9.957

Table 4.26: Current THD with film capacitor at grid condition 2

DC-Link Voltage	**Power Factor**				
	-0.6	**-0.8**	**1**	**0.8**	**0.6**
900	3.317	2.652	2.421	5.05	5.579
800	4.069	3.158	2.557	6.019	7.03
700	5.237	4.051	2.781	7.451	8.872
600	7.155	5.533	3.2	9.672	11.792

Table 4.27: Current THD with film capacitor at grid condition 3

DC-Link Voltage	**Power Factor**				
	-0.6	**-0.8**	**1**	**0.8**	**0.6**
900	3.24	2.56	2.365	4.518	5.342
800	3.91	2.991	2.514	5.319	6.414
700	4.933	3.694	2.744	6.531	8.022
600	6.54	4.863	3.136	8.467	10.643

Table 4.28: Current THD with film capacitor at grid condition 4

DC-Link Voltage	**Power Factor**				
	-0.6	**-0.8**	**1**	**0.8**	**0.6**
900	4.152	3.889	3.7	6.613	7.448
800	4.676	4.249	3.847	7.611	8.761
700	5.761	4.838	4.048	9.084	10.707
600	7.5	5.89	4.438	11.384	13.827

Table 4.29: Current THD with film capacitor at grid condition 5

DC-Link Voltage	Power Factor				
	-0.6	-0.8	1	0.8	0.6
900	2.963	2.476	2.432	4.34	4.944
800	3.51	2.817	2.55	5.102	5.941
700	4.365	3.387	2.726	6.236	7.422
600	5.782	4.396	3.033	8.001	9.781

Table 4.30: Current THD with film capacitor at grid condition 6

DC-Link Voltage	Power Factor				
	-0.6	-0.8	1	0.8	0.6
900	3.713	2.841	2.406	5.26	6.198
800	4.62	3.476	2.587	6.293	7.538
700	5.98	4.488	2.884	7.843	9.548
600	11.568	13.512	20.58	28.55	30.371

Table 4.31: Current THD with film capacitor at grid condition 7

DC-Link Voltage	Power Factor				
	-0.6	-0.8	1	0.8	0.6
900	4.992	4.336	4.343	6.31	7.225
800	5.66	4.754	4.497	7.08	8.307
700	6.636	5.385	4.702	8.248	9.938
600	8.148	6.405	5.021	10.152	12.65

Table 4.32: Current THD with film capacitor at grid condition 8

DC-Link Voltage	Power Factor				
	-0.6	-0.8	1	0.8	0.6
900	1.909	1.314	1.098	2.937	3.604
800	2.462	1.671	1.2	3.569	4.439
700	3.312	2.275	1.412	4.526	5.681
600	4.655	3.271	1.809	6.023	7.665

4.2 Output Current Harmonics and THD with Unbalance Controller

The output current THD and current harmonics are observed to validate the differences between two capacitor types with unbalance controller.

4.2.1 Electrolytic DC-Link Capacitor

The output grid currents of DC/AC converter are given in Table 4.33 - Table 4.36 with respect to the DC-Link voltage. Furthermore, the DC/AC converter output current THDs are given in Table 4.37 - Table 4.44. The DC/AC converter output current THDs also given in Figure 4.18 - Figure 4.25 in 3D form to visualize the structure.

The unbalanced controller decreases the output current ripple and THD ratios. The output current THD is under 1% in all operating conditions. The worst current THD in all grid conditions is observed in 900V DC-Link voltage and 0.6 lagging power factor.

The output current THD is affected negatively when the power factor is lagging. A lagging operation affects the current THD more than a leading or unity power factor operation. Leading power factor improves the THD performance. The output current THD is better than unity and lagging power factor operations at same DC-Link voltage level.

All unbalanced grid conditions, except the eighth condition, have a negative effect on output current THD. There is one hazardous result in the current THD, which is given in grid condition 6. Due to the voltage increase in the two phases of the grid, the DC/AC converter still enters a nonlinear modulation region even if the unbalance controller is implemented. The unbalanced controller has no positive effect in grid condition 6 at 600V DC-Link voltage. The output current THD goes up to 43% at 600V DC-Link voltage. Therefore, this condition is neglected in Figure 4.13. The output current THD is under 1%, and it is in the linear modulation region of the converter. Maximum current THD is observed as 1.01% in the grid condition 7 at 900V DC voltage and 0.6 lagging power factor. The DC/AC converter can handle the unbalanced grid condition without any deflection from the THD standards of a grid-connected converter.

According to IEEE 519-2014, the output current THD of the DC/AC converter is limited to 5% [17]. Therefore, an electrolytic DC-Link capacitor block can handle unbalanced conditions without losing the control ability of the DC/AC converter.

There is an inverse proportion between a DC-Link voltage and an output current THD ratio. A DC-Link voltage is directly related to output current THD. A decrease in the DC-Link voltage increases the current THD ratio of the DC/AC converter.

Moreover, the voltage drops in all phases (symmetrical voltage drops) do not affect the output current THD level. According to Figure 4.9, current THD is under 0.866%, and it is closed to the balance system result. quantity.

For a DC-Link Capacitor block that has high capacitance does not require an unbalance controller. The system is already met with the distributed power system requirements by itself.

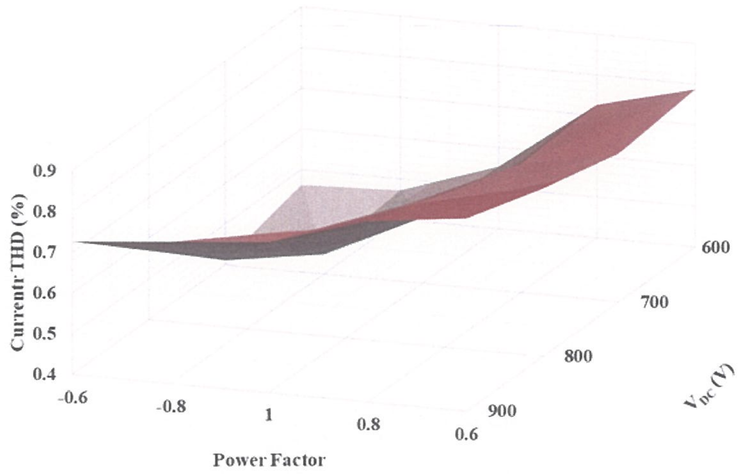

Figure 4.18: Current THD results with Electrolytic DC-Link capacitor and unbalance controller at grid condition 1

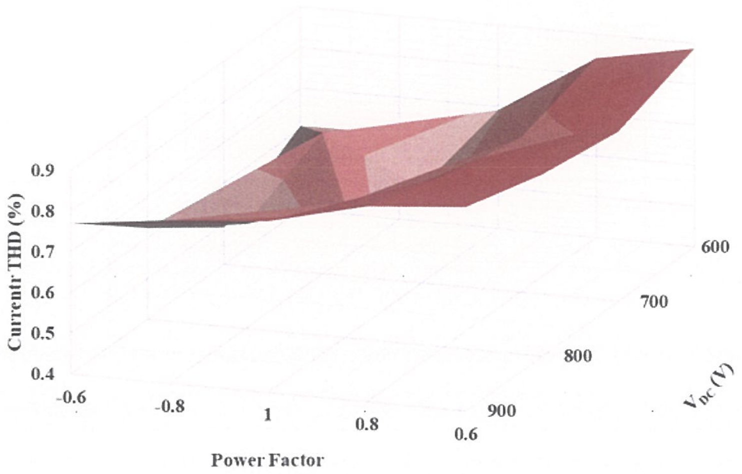

Figure 4.19: Current THD results with Electrolytic DC-Link capacitor and unbalance controller at grid condition 2

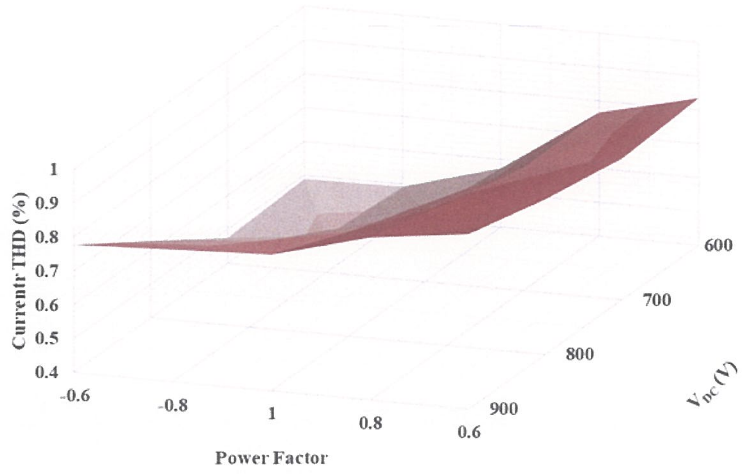

Figure 4.20: Current THD results with Electrolytic DC-Link capacitor and unbalance controller at grid condition 3

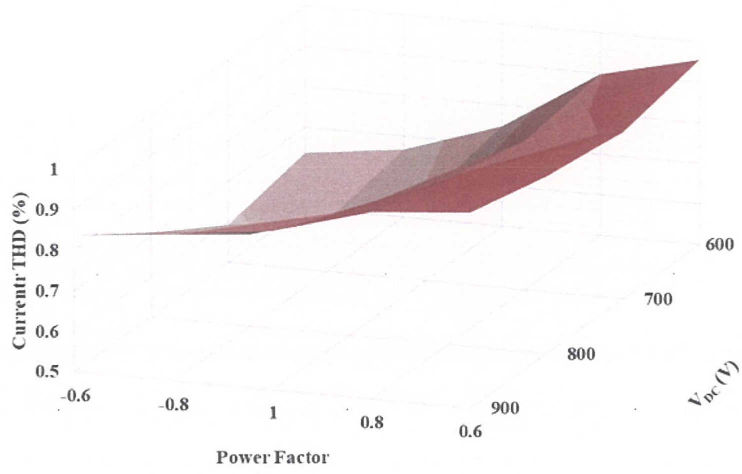

Figure 4.21: Current THD results with Electrolytic DC-Link capacitor and unbalance controller at grid condition 4

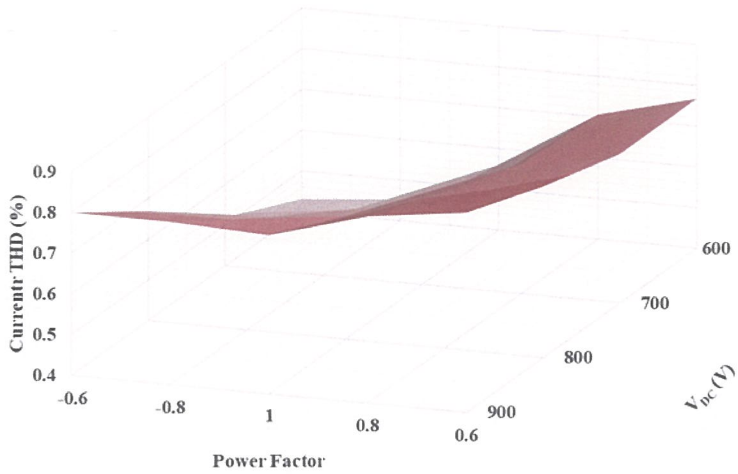

Figure 4.22: Current THD results with Electrolytic DC-Link capacitor and unbalance controller at grid condition 5

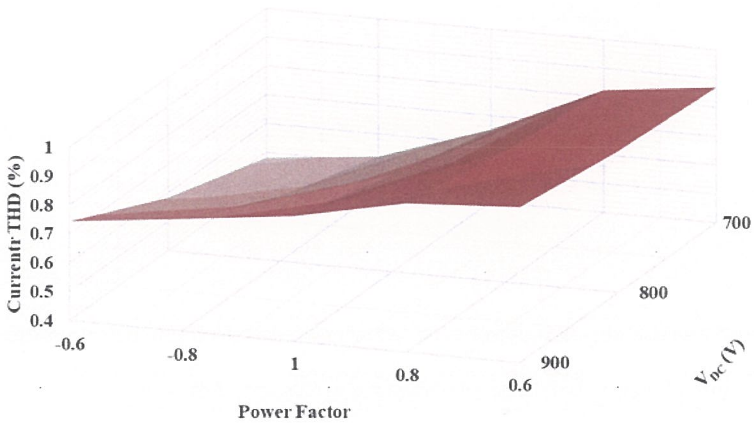

Figure 4.23: Current THD results with Electrolytic DC-Link capacitor and unbalance controller at grid condition 6

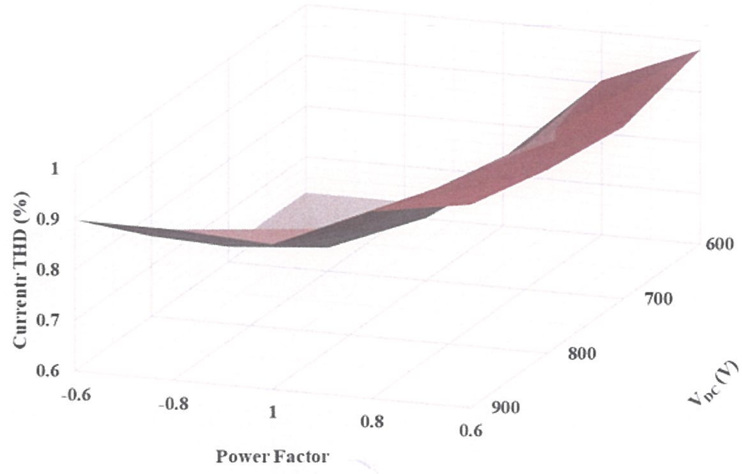

Figure 4.24: Current THD results with Electrolytic DC-Link capacitor and unbalance controller at grid condition 7

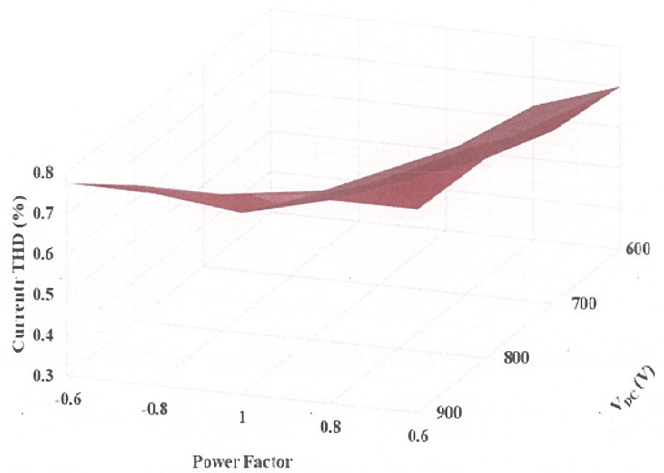

Figure 4.25: Current THD results with Electrolytic DC-Link capacitor and unbalance controller at grid condition 8

Table 4.33: Output currents with unbalance controller at 900V

Power Factor	Grid Conditions	I_f	I_{3f}	I_{5f}	I_{7f}	I_{11f}	I_{13f}	$I_{f_{sw}}$	$I_{f_{2sw}}$
1	1	14.76341	7.75E-05	0.072328	0.047503	0.014878	0.00743	0.063245	0.007664
1	2	14.48127	0.032482	0.075218	0.052984	0.016847	0.011348	0.060712	0.010506
1	3	15.60904	0.035264	0.077418	0.046134	0.015606	0.008992	0.072819	0.008306
1	4	15.29188	0.065592	0.079857	0.052344	0.018303	0.01217	0.067393	0.009819
1	5	16.02585	0.036144	0.073112	0.046585	0.013213	0.009348	0.079318	0.007581
1	6	14.12426	0.031227	0.078055	0.052204	0.019611	0.01107	0.055802	0.011339
1	7	16.56727	0.072807	0.081361	0.045034	0.017353	0.009223	0.082809	0.007818
1	8	16.39275	8.69E-05	0.069105	0.039276	0.01142	0.00704	0.084456	0.006839
0.8	1	15.1517	9.59E-05	0.085226	0.058613	0.018806	0.009169	0.062816	0.00944
0.8	2	15.03698	0.031586	0.091106	0.067509	0.021089	0.012487	0.059462	0.010972
0.8	3	15.72702	0.034233	0.093377	0.05855	0.019355	0.009596	0.071539	0.008723
0.8	4	15.58925	0.064053	0.097732	0.066006	0.022255	0.013276	0.065978	0.0103
0.8	5	15.91424	0.032836	0.08697	0.058556	0.016653	0.010368	0.078269	0.007917
0.8	6	14.88983	0.032954	0.096812	0.067167	0.024242	0.011817	0.054581	0.011826
0.8	7	16.39515	0.070833	0.099554	0.05595	0.020674	0.009894	0.081434	0.008165
0.8	8	16.08824	7.87E-05	0.080287	0.049932	0.014555	0.007582	0.083749	0.007083
-0.8	1	13.89796	6.68E-05	0.061915	0.036181	0.011945	0.008094	0.065088	0.008666
-0.8	2	13.77012	0.031689	0.063903	0.042592	0.013758	0.010553	0.061746	0.010194
-0.8	3	14.60986	0.034691	0.065621	0.037242	0.012775	0.008634	0.073911	0.007978
-0.8	4	14.45783	0.061398	0.066629	0.042339	0.01541	0.011369	0.06861	0.009484
-0.8	5	14.83411	0.035843	0.06372	0.038016	0.010737	0.008761	0.080149	0.007345
-0.8	6	13.58975	0.030225	0.064222	0.041552	0.016245	0.010542	0.056897	0.011079
-0.8	7	15.41256	0.071562	0.068031	0.037905	0.014683	0.00875	0.083978	0.007563
-0.8	8	15.02398	4.95E-05	0.060879	0.031548	0.009142	0.006782	0.085082	0.006674
0.6	1	15.14837	7.11E-05	0.089277	0.062526	0.019955	0.009522	0.062592	0.009572
0.6	2	15.15508	0.031005	0.096126	0.071764	0.022421	0.012987	0.059235	0.01106
0.6	3	15.57157	0.033323	0.098107	0.062174	0.020518	0.009971	0.071294	0.008876
0.6	4	15.5547	0.060663	0.10297	0.069952	0.023571	0.013808	0.06573	0.010406
0.6	5	15.62213	0.031471	0.091271	0.06213	0.017742	0.01081	0.078036	0.008089
0.6	6	15.12448	0.032729	0.102319	0.071451	0.025662	0.012253	0.054355	0.011838
0.6	7	16.06821	0.068641	0.104949	0.059226	0.021721	0.01023	0.081218	0.008305
0.6	8	15.63786	7.51E-05	0.083696	0.053148	0.015546	0.007845	0.083519	0.007259
-0.6	1	13.89527	5.95E-05	0.058431	0.032968	0.010952	0.00806	0.065548	0.008622
-0.6	2	13.88418	0.031094	0.05993	0.039008	0.012651	0.010401	0.062229	0.010166
-0.6	3	14.48469	0.034019	0.061453	0.034408	0.011807	0.008571	0.074393	0.007921
-0.6	4	14.46124	0.059425	0.062007	0.038793	0.014397	0.01119	0.069189	0.009365
-0.6	5	14.54678	0.035217	0.060375	0.035043	0.009931	0.008624	0.080512	0.007276
-0.6	6	13.85009	0.029596	0.059381	0.038121	0.015026	0.01052	0.05745	0.011061
-0.6	7	15.14934	0.070085	0.063427	0.035719	0.013729	0.008682	0.084484	0.00755
-0.6	8	14.59104	4.14E-05	0.057901	0.028869	0.00844	0.00673	0.085361	0.006627

Table 4.34: Output with currents unbalance controller at 800V

Power Factor	Grid Conditions	I_f	I_{3f}	I_{5f}	I_{7f}	I_{11f}	I_{13f}	$I_{f_{sw}}$	$I_{f_{2sw}}$
1	1	14.41728	6.76E-05	0.062123	0.047148	0.017534	0.009814	0.043175	0.011362
1	2	14.14159	0.030626	0.063851	0.054728	0.019789	0.013113	0.040924	0.012417
1	3	15.24377	0.033824	0.069568	0.047915	0.018533	0.010362	0.049536	0.010851
1	4	14.93351	0.063168	0.070621	0.054205	0.021322	0.01401	0.045803	0.012097
1	5	15.65128	0.034507	0.066791	0.04837	0.015567	0.010549	0.055794	0.010217
1	6	13.79145	0.031182	0.064223	0.053859	0.023063	0.012801	0.03781	0.012725
1	7	16.18103	0.070813	0.075125	0.046707	0.020223	0.010396	0.057766	0.010312
1	8	16.00865	8.26E-05	0.06366	0.041075	0.013517	0.007625	0.062517	0.009339
0.8	1	15.03259	7.87E-05	0.078514	0.063531	0.022531	0.010604	0.042149	0.011743
0.8	2	14.91614	0.03321	0.083008	0.072936	0.02516	0.014504	0.039945	0.012715
0.8	3	15.60369	0.035858	0.089315	0.063409	0.023286	0.011139	0.048376	0.011264
0.8	4	15.46334	0.064968	0.092895	0.071346	0.026303	0.015418	0.04473	0.012448
0.8	5	15.78875	0.034227	0.083484	0.063305	0.019962	0.011817	0.054478	0.010612
0.8	6	14.7718	0.034789	0.087338	0.072602	0.028887	0.013745	0.037	0.012897
0.8	7	16.26531	0.074097	0.097737	0.060537	0.024444	0.011341	0.056285	0.010757
0.8	8	16.74337	7.6E-05	0.078831	0.055928	0.018025	0.008386	0.060927	0.009834
-0.8	1	13.91746	6.4E-05	0.049843	0.03534	0.013808	0.009249	0.044078	0.0111
-0.8	2	13.78731	0.028546	0.049757	0.04157	0.015821	0.012055	0.041816	0.012277
-0.8	3	14.63127	0.031466	0.054875	0.036531	0.014889	0.009761	0.050587	0.010573
-0.8	4	14.47598	0.0577	0.054201	0.041569	0.017645	0.012902	0.046774	0.011905
-0.8	5	14.85444	0.033225	0.055049	0.037625	0.012342	0.009692	0.056826	0.009908
-0.8	6	13.60737	0.028961	0.047102	0.040253	0.018721	0.012098	0.038558	0.012646
-0.8	7	15.437	0.06574	0.058552	0.037352	0.016911	0.009676	0.059054	0.010017
-0.8	8	15.04607	7.17E-05	0.053436	0.031461	0.010516	0.007201	0.063742	0.008999
0.6	1	15.13403	5.68E-05	0.083516	0.068454	0.023963	0.010953	0.04191	0.011728
0.6	2	15.13558	0.033331	0.089246	0.078348	0.02675	0.01499	0.039712	0.01267
0.6	3	15.55701	0.035522	0.095278	0.067993	0.024673	0.01153	0.048135	0.011308
0.6	4	15.53739	0.062589	0.099497	0.076408	0.027818	0.01595	0.04456	0.012426
0.6	5	15.60767	0.033453	0.088875	0.067873	0.021227	0.012355	0.054278	0.010769
0.6	6	15.11099	0.035312	0.094236	0.078095	0.030608	0.014071	0.036808	0.012858
0.6	7	16.05157	0.073138	0.104581	0.064541	0.025687	0.011741	0.055997	0.010756
0.6	8	15.62031	7.46E-05	0.081539	0.058466	0.018745	0.008665	0.060876	0.009979
-0.6	1	13.84138	7.59E-05	0.045542	0.031356	0.012423	0.009187	0.044526	0.011132
-0.6	2	13.83206	0.027857	0.044883	0.037087	0.014309	0.011815	0.042246	0.01227
-0.6	3	14.42736	0.030389	0.049738	0.033039	0.013515	0.009646	0.051128	0.010567
-0.6	4	14.40624	0.055216	0.048555	0.037125	0.016244	0.012599	0.047283	0.011885
-0.6	5	14.48983	0.031873	0.050941	0.03397	0.011155	0.009479	0.05741	0.009886
-0.6	6	13.80258	0.028335	0.041233	0.035932	0.017078	0.011973	0.038923	0.012629
-0.6	7	15.09026	0.063286	0.052953	0.034655	0.015601	0.009536	0.059666	0.009955
-0.6	8	14.52843	4.27E-05	0.049816	0.028174	0.009445	0.007103	0.064334	0.008916

Table 4.35: Output currents with unbalance controller at 700V

Power Factor	Grid Conditions	I_f	I_{3f}	I_{5f}	I_{7f}	I_{11f}	I_{13f}	$I_{f_{sw}}$	$I_{f_{2sw}}$
1	1	14.4567	5.13E-05	0.042624	0.048441	0.021306	0.011311	0.031523	0.011335
1	2	14.1763	0.031216	0.04194	0.055675	0.024123	0.015186	0.035645	0.011053
1	3	15.28266	0.034381	0.053451	0.049496	0.022218	0.012134	0.034281	0.011961
1	4	14.9672	0.059469	0.05199	0.055612	0.025295	0.016239	0.037582	0.011833
1	5	15.69127	0.033731	0.053944	0.050092	0.018655	0.012367	0.036055	0.011913
1	6	13.8238	0.031982	0.038009	0.054547	0.028253	0.015046	0.042004	0.010625
1	7	16.22138	0.072347	0.0621	0.048386	0.023771	0.012297	0.038849	0.01213
1	8	16.05185	5.95E-05	0.052721	0.042676	0.016326	0.008983	0.039759	0.011755
0.8	1	15.0486	5.2E-05	0.063593	0.069879	0.027901	0.012341	0.031704	0.011246
0.8	2	14.92423	0.035951	0.066728	0.079446	0.031187	0.017045	0.036472	0.010884
0.8	3	15.61994	0.038338	0.078801	0.069702	0.028476	0.013249	0.034157	0.012004
0.8	4	15.47234	0.065965	0.081043	0.07792	0.031845	0.018143	0.038208	0.01177
0.8	5	15.80249	0.036434	0.074522	0.069645	0.02437	0.013987	0.035291	0.012067
0.8	6	14.78214	0.037777	0.068035	0.078987	0.035915	0.016366	0.043335	0.010399
0.8	7	16.28058	0.079193	0.091386	0.066356	0.029316	0.013635	0.038389	0.012368
0.8	8	15.97842	4.42E-05	0.070068	0.060025	0.021682	0.009843	0.038696	0.012017
-0.8	1	13.94018	4.53E-05	0.026883	0.033048	0.016272	0.0106	0.031447	0.011418
-0.8	2	13.81072	0.028145	0.023243	0.038555	0.018743	0.013804	0.034922	0.011205
-0.8	3	14.65456	0.031323	0.034725	0.034591	0.017411	0.01133	0.034495	0.011932
-0.8	4	14.49867	0.050619	0.030759	0.039181	0.020397	0.014792	0.037168	0.01184
-0.8	5	14.87876	0.03089	0.038772	0.036005	0.014354	0.011226	0.036757	0.011799
-0.8	6	13.62711	0.028863	0.01604	0.036556	0.022337	0.014037	0.040794	0.010765
-0.8	7	15.46119	0.066097	0.041109	0.035513	0.019512	0.011285	0.039326	0.011918
-0.8	8	15.07288	5.14E-05	0.039721	0.030136	0.012317	0.008434	0.040757	0.011557
0.6	1	15.20603	3E-05	0.069939	0.076468	0.029848	0.012685	0.031761	0.011201
0.6	2	15.2059	0.036911	0.073952	0.086717	0.03331	0.017628	0.036668	0.010821
0.6	3	15.6282	0.038782	0.086486	0.0758	0.030299	0.013589	0.03415	0.011992
0.6	4	15.60253	0.064981	0.089671	0.084678	0.033775	0.018679	0.038394	0.011724
0.6	5	15.68298	0.036446	0.081462	0.075662	0.026027	0.014524	0.035145	0.012078
0.6	6	15.18257	0.039192	0.077061	0.086399	0.038164	0.016717	0.043677	0.010335
0.6	7	16.12566	0.079767	0.100383	0.071715	0.030888	0.014041	0.038281	0.012374
0.6	8	15.69125	5.11E-05	0.07537	0.065392	0.023201	0.010183	0.038482	0.012104
-0.6	1	15.32615	3.93E-05	0.021159	0.027709	0.014432	0.010337	0.031449	0.011402
-0.6	2	15.2627	0.029662	0.017267	0.032595	0.016722	0.01329	0.034679	0.011229
-0.6	3	16.02035	0.032831	0.028233	0.029705	0.015624	0.011022	0.034586	0.011898
-0.6	4	15.93584	0.051313	0.024188	0.033367	0.01854	0.014248	0.037004	0.011825
-0.6	5	14.48244	0.029726	0.033708	0.031335	0.012773	0.010882	0.037058	0.011762
-0.6	6	13.7969	0.028337	0.011214	0.031123	0.02019	0.013754	0.040293	0.010799
-0.6	7	15.08192	0.063849	0.034602	0.03206	0.017836	0.011009	0.039543	0.011903
-0.6	8	14.5172	4.86E-05	0.035199	0.025987	0.010856	0.008315	0.041215	0.011505

Table 4.36: Output currents with unbalance controller at 600V

Power Factor	Grid Conditions	I_f	I_{3f}	I_{5f}	I_{7f}	I_{11f}	I_{13f}	$I_{f_{sw}}$	$I_{f_{2sw}}$
1	1	14.4567	5.13E-05	0.042624	0.048441	0.021306	0.011311	0.031523	0.011335
1	2	14.1763	0.031216	0.04194	0.055675	0.024123	0.015186	0.035645	0.011053
1	3	15.28266	0.034381	0.053451	0.049496	0.022218	0.012134	0.034281	0.011961
1	4	14.9672	0.059469	0.05199	0.055612	0.025295	0.016239	0.037582	0.011833
1	5	15.69127	0.033731	0.053944	0.050092	0.018655	0.012367	0.036055	0.011913
1	6	13.8238	0.031982	0.038009	0.054547	0.028253	0.015046	0.042004	0.010625
1	7	16.22138	0.072347	0.0621	0.048386	0.023771	0.012297	0.038849	0.01213
1	8	16.05185	5.95E-05	0.052721	0.042676	0.016326	0.008983	0.039759	0.011755
0.8	1	15.0486	5.2E-05	0.063593	0.069879	0.027901	0.012341	0.031704	0.011246
0.8	2	14.92423	0.035951	0.066728	0.079446	0.031187	0.017045	0.036472	0.010884
0.8	3	15.61994	0.038338	0.078801	0.069702	0.028476	0.013249	0.034157	0.012004
0.8	4	15.47234	0.065965	0.081043	0.07792	0.031845	0.018143	0.038208	0.01177
0.8	5	15.80249	0.036434	0.074522	0.069645	0.02437	0.013987	0.035291	0.012067
0.8	6	14.78214	0.037777	0.068035	0.078987	0.035915	0.016366	0.043335	0.010399
0.8	7	16.28058	0.079193	0.091386	0.066356	0.029316	0.013635	0.038389	0.012368
0.8	8	15.97842	4.42E-05	0.070068	0.060025	0.021682	0.009843	0.038696	0.012017
-0.8	1	13.94018	4.53E-05	0.026883	0.033048	0.016272	0.0106	0.031447	0.011418
-0.8	2	13.81072	0.028145	0.023243	0.038555	0.018743	0.013804	0.034922	0.011205
-0.8	3	14.65456	0.031323	0.034725	0.034591	0.017411	0.01133	0.034495	0.011932
-0.8	4	14.49867	0.050619	0.030759	0.039181	0.020397	0.014792	0.037168	0.01184
-0.8	5	14.87876	0.03089	0.038772	0.036005	0.014354	0.011226	0.036757	0.011799
-0.8	6	13.62711	0.028863	0.01604	0.036556	0.022337	0.014037	0.040794	0.010765
-0.8	7	15.46119	0.066097	0.041109	0.035513	0.019512	0.011285	0.039326	0.011918
-0.8	8	15.07288	5.14E-05	0.039721	0.030136	0.012317	0.008434	0.040757	0.011557
0.6	1	15.20603	3E-05	0.069939	0.076468	0.029848	0.012685	0.031761	0.011201
0.6	2	15.2059	0.036911	0.073952	0.086717	0.03331	0.017628	0.036668	0.010821
0.6	3	15.6282	0.038782	0.086486	0.0758	0.030299	0.013589	0.03415	0.011992
0.6	4	15.60253	0.064981	0.089671	0.084678	0.033775	0.018679	0.038394	0.011724
0.6	5	15.68298	0.036446	0.081462	0.075662	0.026027	0.014524	0.035145	0.012078
0.6	6	15.18257	0.039192	0.077061	0.086399	0.038164	0.016717	0.043677	0.010335
0.6	7	16.12566	0.079767	0.100383	0.071715	0.030888	0.014041	0.038281	0.012374
0.6	8	15.69125	5.11E-05	0.07537	0.065392	0.023201	0.010183	0.038482	0.012104
-0.6	1	15.32615	3.93E-05	0.021159	0.027709	0.014432	0.010337	0.031449	0.011402
-0.6	2	15.2627	0.029662	0.017267	0.032595	0.016722	0.01329	0.034679	0.011229
-0.6	3	16.02035	0.032831	0.028233	0.029705	0.015624	0.011022	0.034586	0.011898
-0.6	4	15.93584	0.051313	0.024188	0.033367	0.01854	0.014248	0.037004	0.011825
-0.6	5	14.48244	0.029726	0.033708	0.031335	0.012773	0.010882	0.037058	0.011762
-0.6	6	13.7969	0.028337	0.011214	0.031123	0.02019	0.013754	0.040293	0.010799
-0.6	7	15.08192	0.063849	0.034602	0.03206	0.017836	0.011009	0.039543	0.011903
-0.6	8	14.5172	4.86E-05	0.035199	0.025987	0.010856	0.008315	0.041215	0.011505

Table 4.37: Current THD with electrolytic DC-Link capacitor and unbalance controller at grid condition 1

DC-Link Voltage	Power Factor				
	-0.6	**-0.8**	**1**	**0.8**	**0.6**
900	0.726	0.748	0.77	0.844	0.873
800	0.569	0.6	0.674	0.776	0.812
700	0.411	0.448	0.561	0.716	0.764
600	0.463	0.472	0.553	0.727	0.787

Table 4.38: Current THD with electrolytic DC-Link capacitor and unbalance controller at grid condition 2

DC-Link Voltage	Power Factor				
	-0.6	**-0.8**	**1**	**0.8**	**0.6**
900	0.77	0.8	0.82	0.879	0.9
800	0.624	0.656	0.731	0.819	0.846
700	0.491	0.746	0.636	0.779	0.817
600	0.607	0.61	0.691	0.841	0.887

Table 4.39: Current THD with electrolytic DC-Link capacitor and unbalance controller at grid condition 3

DC-Link Voltage	Power Factor				
	-0.6	**-0.8**	**1**	**0.8**	**0.6**
900	0.777	0.79	0.802	0.88	0.917
800	0.628	0.646	0.708	0.818	0.858
700	0.475	0.507	0.602	0.763	0.817
600	0.489	0.493	0.574	0.766	0.835

Table 4.40: Current THD with electrolytic DC-Link capacitor and unbalance controller at grid condition 4

DC-Link Voltage	Power Factor				
	-0.6	**-0.8**	**1**	**0.8**	**0.6**
900	0.836	0.86	0.891	0.96	0.981
800	0.708	0.726	0.805	0.906	0.936
700	0.593	0.626	0.706	0.867	0.911
600	0.637	0.667	0.747	0.898	0.956

Table 4.41: Current THD with electrolytic DC-Link capacitor and unbalance controller at grid condition 5

DC-Link Voltage	Power Factor				
	-0.6	**-0.8**	**1**	**0.8**	**0.6**
900	0.799	0.799	0.789	0.858	0.89
800	0.669	0.673	0.702	0.783	0.82
700	0.52	0.539	0.6	0.718	0.766
600	0.431	0.453	0.56	0.706	0.767

Table 4.42: Current THD with electrolytic DC-Link capacitor and unbalance controller at grid condition 6

DC-Link Voltage	Power Factor				
	-0.6	**-0.8**	**1**	**0.8**	**0.6**
900	0.743	0.787	0.834	0.914	0.937
800	0.584	0.626	0.734	0.856	0.89
700	0.481	0.521	0.651	0.824	0.869
600	13.18	17.64	27.97	42.92	46.1

Table 4.43: Current THD with electrolytic DC-Link capacitor and unbalance controller at grid condition 7

DC-Link Voltage	Power Factor				
	-0.6	**-0.8**	**1**	**0.8**	**0.6**
900	0.897	0.897	0.886	0.969	1.01
800	0.758	0.767	0.809	0.916	0.961
700	0.63	0.646	0.723	0.883	0.939
600	0.63	0.63	0.7	0.905	0.983

Table 4.44: Current THD with electrolytic DC-Link capacitor and unbalance controller at grid condition 8

DC-Link Voltage	Power Factor				
	-0.6	**-0.8**	**1**	**0.8**	**0.6**
900	0.774	0.771	0.746	0.822	0.866
800	0.636	0.636	0.657	0.72	0.791
700	0.47	0.481	0.539	0.672	0.725
600	0.342	0.361	0.451	0.631	0.701

4.2.2 Film DC-Link Capacitor

The electrolytic capacitor block model is modified with the film capacitor DC-Link block model in the simulation to examine the results. Unbalance controller is also activated in this section. Same power factor and DC-Link voltage variations are considered in this case. The output grid currents of DC/AC converter with Film DC-Link capacitor block are given in Table 4.45 - Table 4.48 with respect to the DC-Link voltage. Furthermore, the DC/AC converter output current THDs are given in Table 4.49 - Table 4.56. The DC/AC converter output current THDs also given in Figure 4.26 - Figure 4.27 in 3D form to visualize the structure.

The decrease in the capacitance of the DC-Link with the changing capacitor type, the output current THDs become worse than an electrolytic DC-Link capacitor. However, because of unbalance controller, the output current THDs are better. Except for three linear operating conditions, system stability is performed by film capacitors with the implementation of unbalance controller. Furthermore, almost all current THD results are under the IEEE 519-2014 THD limit. Only three operating conditions, which are, grid condition 7 - 600V - 0.6 lagging power factor, grid condition 4 - 600V - 0.6 lagging power factor, and grid condition 2 - 600V - 0.6 lagging power factor, do not meet with the distributed power system requirements. The output current THD goes up to 5.56%, and it breaks the boundary closely. Therefore, the unbalance controller makes capacitor wisely as DC-Link capacitor for the application that the DC-Link capacitor will be changed from the electrolytic capacitor to the film capacitor.

Output current THDs still is not as good as an electrolytic capacitor with film capacitor but most of the current THDs are under the IEEE 519-2014 THD limits. There is an inverse proportion between a DC-Link voltage and an output current THD ratio. The decrease in the DC-Link voltage rises the output current THDs. Furthermore, the output current THDs at leading power factors are better than lagging power factor.

There is also a nonlinear modulation region problem exists under the grid condition 6 at 600V DC-Link voltage. DC/AC converter enters over-modulation because of a 10% increase on two phases of the grid voltages. Therefore this condition does not exist in Figure 4.25.

In addition, especially low order harmonic ripples decrease with the implementation of unbalance controller. The output current of the DC/AC converter is more pure with the injected compensation current, especially in unbalanced grid conditions.

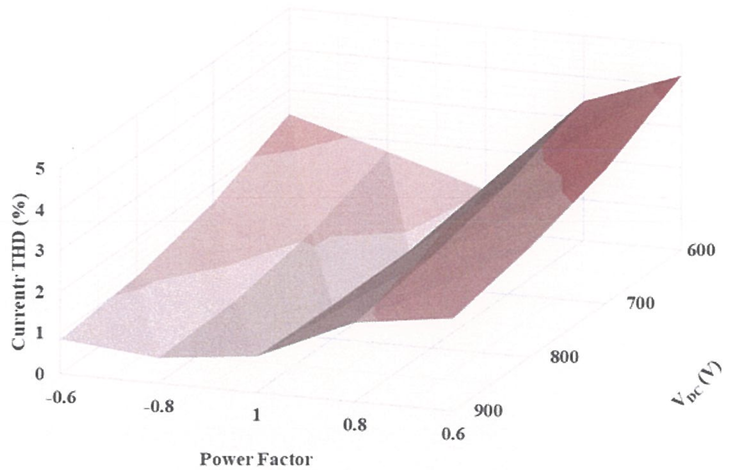

Figure 4.26: Current THD results with Film DC-Link capacitor and unbalance controller at grid condition 1

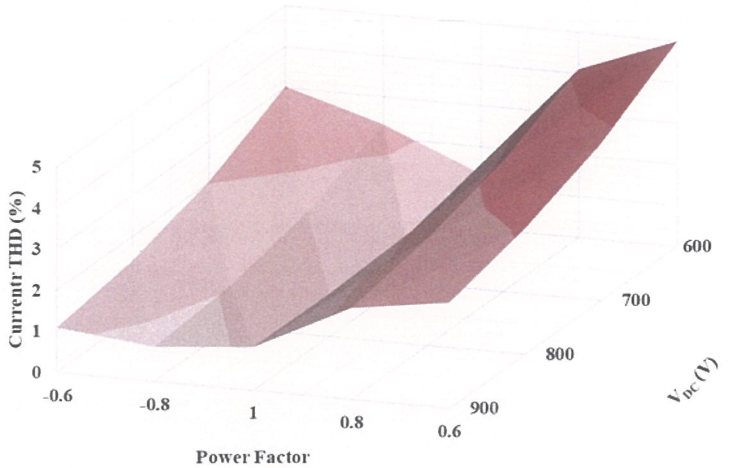

Figure 4.27: Current THD results with Film DC-Link capacitor and unbalance controller at grid condition 2

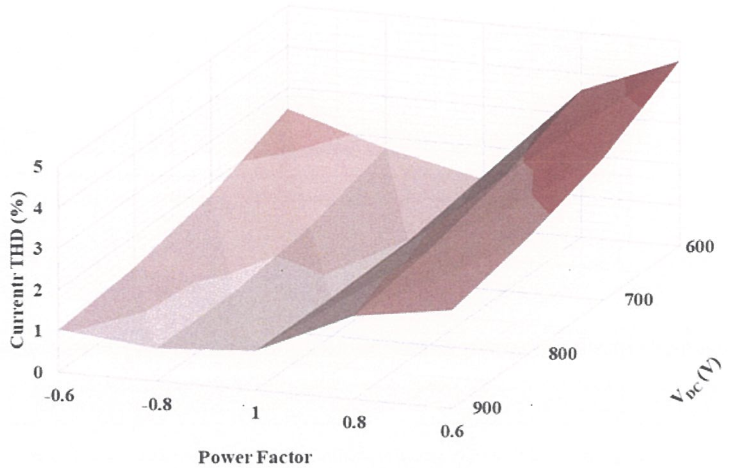

Figure 4.28: Current THD results with Film DC-Link capacitor and unbalance controller at grid condition 3

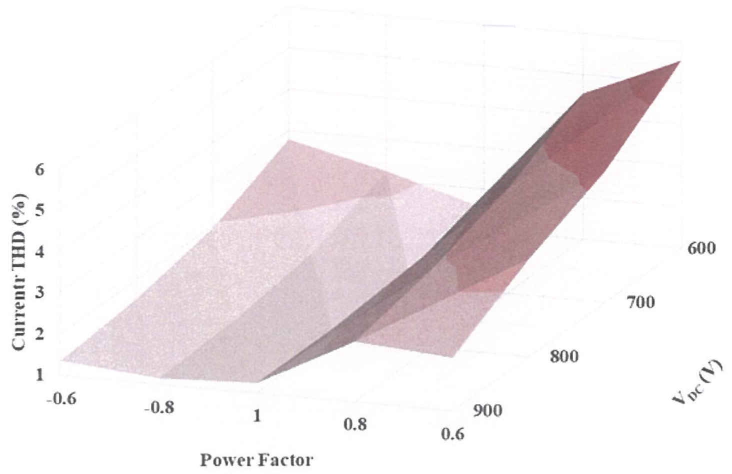

Figure 4.29: Current THD results with Film DC-Link capacitor and unbalance controller at grid condition 4

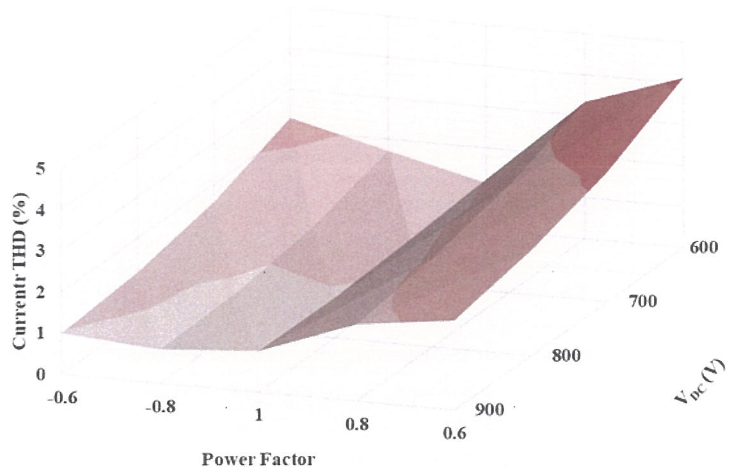

Figure 4.30: Current THD results with Film DC-Link capacitor and unbalance controller at grid condition 5

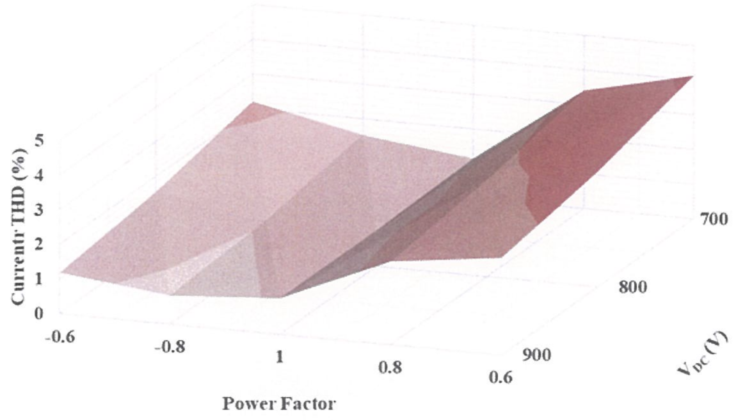

Figure 4.31: Current THD results with Film DC-Link capacitor and unbalance controller at grid condition 6

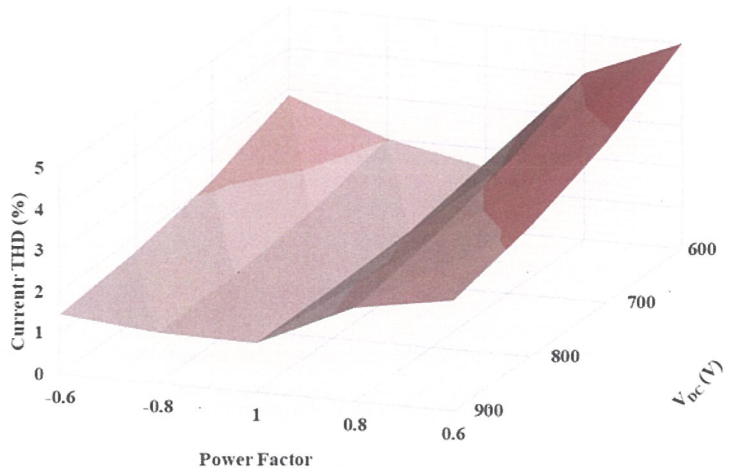

Figure 4.32: Current THD results with Film DC-Link capacitor and unbalance controller at grid condition 7

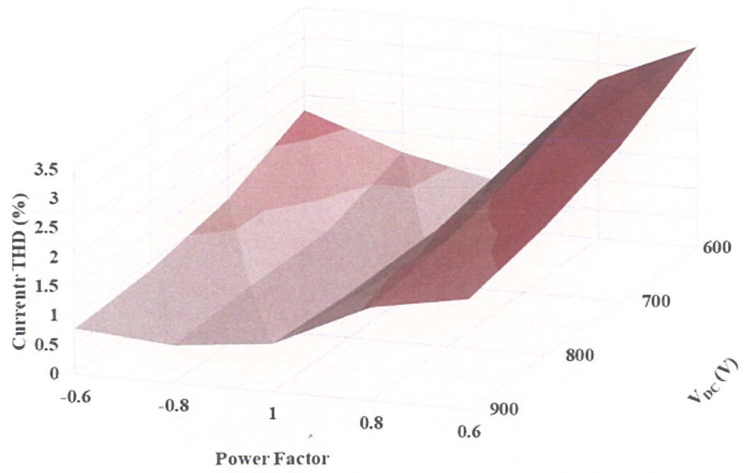

Figure 4.33: Current THD results with Film DC-Link capacitor and unbalance controller at grid condition 8

Table 4.45: Output currents with unbalance controller at 900V

Power Factor	Grid Conditions	I_f	I_{3f}	I_{5f}	I_{7f}	I_{11f}	I_{13f}	$I_{f_{sw}}$	$I_{f_{2sw}}$
1	1	14.46306	0.000129	0.085151	0.054036	0.01568	0.004688	0.064505	0.008982
1	2	14.15378	0.064567	0.09856	0.062132	0.017202	0.007571	0.061214	0.010495
1	3	15.29379	0.068242	0.090417	0.05651	0.016509	0.005838	0.073266	0.008284
1	4	14.94963	0.12084	0.104216	0.062852	0.018254	0.009365	0.067494	0.009798
1	5	15.69269	0.071522	0.093729	0.054099	0.014131	0.006256	0.07993	0.00754
1	6	13.84076	0.061209	0.093554	0.064151	0.019923	0.007389	0.056347	0.01132
1	7	16.23338	0.140491	0.09449	0.057446	0.019357	0.00667	0.083212	0.007823
1	8	16.06003	0.000103	0.079907	0.046431	0.012551	0.003795	0.085027	0.006819
0.8	1	15.07384	0.000113	0.212377	0.174379	0.048733	0.006707	0.066421	0.009318
0.8	2	14.98163	0.082229	0.252143	0.19693	0.051761	0.01376	0.063342	0.010927
0.8	3	15.64303	0.090757	0.245103	0.169778	0.046446	0.011214	0.074855	0.008616
0.8	4	15.44926	0.176384	0.283891	0.189407	0.047306	0.018027	0.069713	0.010272
0.8	5	15.87441	0.083153	0.219347	0.164342	0.041834	0.01188	0.081927	0.00772
0.8	6	14.81041	0.089877	0.278281	0.202486	0.056785	0.013293	0.058135	0.011751
0.8	7	16.29633	0.190041	0.274407	0.158046	0.043777	0.014999	0.084286	0.008066
0.8	8	16.00823	9.02E-05	0.182833	0.143534	0.039083	0.005541	0.087676	0.006914
-0.8	1	13.9716	0.00012	0.023534	0.034829	0.01428	0.001248	0.06386	0.008731
-0.8	2	13.843	0.069337	0.046605	0.038028	0.014577	0.003516	0.060659	0.0102
-0.8	3	14.70526	0.07233	0.036425	0.032452	0.012712	0.003585	0.072759	0.008029
-0.8	4	14.52797	0.12454	0.052041	0.033789	0.012374	0.005604	0.067445	0.009478
-0.8	5	14.93767	0.074181	0.030177	0.029838	0.012662	0.002901	0.078929	0.007456
-0.8	6	13.67823	0.068331	0.049167	0.040943	0.014658	0.004216	0.05606	0.011112
-0.8	7	15.53055	0.147637	0.052376	0.031186	0.009481	0.006135	0.083098	0.007745
-0.8	8	15.10949	0.000104	0.013237	0.026598	0.012425	0.000937	0.083588	0.006779
0.6	1	15.17516	8.92E-05	0.2501	0.211282	0.058124	0.006675	0.067266	0.00941
0.6	2	15.22941	0.089534	0.296931	0.237782	0.061293	0.01479	0.064368	0.011018
0.6	3	15.59869	0.098213	0.291156	0.20383	0.054618	0.011897	0.07556	0.008731
0.6	4	15.52215	0.18262	0.336825	0.227168	0.055492	0.019666	0.070966	0.010385
0.6	5	15.70494	0.088026	0.255476	0.197516	0.049493	0.012992	0.082741	0.007899
0.6	6	15.15996	0.099785	0.333849	0.24443	0.066731	0.013857	0.059044	0.011781
0.6	7	16.0899	0.205071	0.328545	0.188047	0.050333	0.01686	0.084864	0.008169
0.6	8	15.6678	7.33E-05	0.212951	0.173022	0.046669	0.005641	0.088572	0.007052
-0.6	1	13.89498	0.000112	0.056496	0.066753	0.025159	0.002868	0.06389	0.008723
-0.6	2	13.92959	0.074113	0.088277	0.074412	0.026118	0.006248	0.060823	0.010197
-0.6	3	14.50675	0.078538	0.072167	0.06078	0.022862	0.005961	0.072769	0.008022
-0.6	4	14.4568	0.143103	0.085323	0.068054	0.021017	0.008382	0.067727	0.009374
-0.6	5	14.60355	0.076213	0.064326	0.05921	0.021901	0.005336	0.078744	0.007461
-0.6	6	13.87767	0.078596	0.098829	0.076253	0.027015	0.006778	0.056403	0.011129
-0.6	7	15.1908	0.163643	0.090145	0.052449	0.015603	0.00803	0.083275	0.007818
-0.6	8	14.59166	6.87E-05	0.036008	0.052881	0.021134	0.002391	0.083223	0.006771

Table 4.46: Output currents with unbalance controller at 800V

Power Factor	Grid Conditions	I_f	I_{3f}	I_{5f}	I_{7f}	I_{11f}	I_{13f}	$I_{f_{sw}}$	$I_{f_{2sw}}$
1	1	14.43886	0.000142	0.084275	0.060557	0.019865	0.006422	0.043513	0.011343
1	2	14.13652	0.069699	0.09849	0.069196	0.021788	0.009688	0.041296	0.012422
1	3	15.27237	0.073544	0.091106	0.063573	0.020932	0.007915	0.049904	0.010824
1	4	14.92312	0.128424	0.105349	0.070477	0.022616	0.011842	0.046091	0.012082
1	5	15.67599	0.077645	0.096536	0.060563	0.018371	0.008095	0.056328	0.010217
1	6	13.81982	0.065458	0.092996	0.071911	0.02477	0.009572	0.038115	0.012725
1	7	16.21535	0.151418	0.095038	0.06517	0.023751	0.008706	0.058079	0.010279
1	8	16.03354	0.000127	0.081251	0.052514	0.016288	0.005149	0.063058	0.009318
0.8	1	15.06509	9.15E-05	0.242888	0.21301	0.060543	0.008094	0.044953	0.011661
0.8	2	14.98398	0.09405	0.292547	0.239751	0.064476	0.01627	0.042405	0.012672
0.8	3	15.63578	0.103219	0.285285	0.206994	0.057377	0.014241	0.051178	0.011201
0.8	4	15.43181	0.20456	0.333923	0.230513	0.057522	0.022027	0.047944	0.012429
0.8	5	15.87169	0.093422	0.255705	0.199615	0.052475	0.014018	0.05809	0.010582
0.8	6	14.8031	0.103105	0.321891	0.247295	0.069672	0.0165	0.038442	0.012814
0.8	7	16.28817	0.216428	0.323844	0.192622	0.053104	0.019195	0.058672	0.010699
0.8	8	15.99766	0.000114	0.209826	0.17524	0.048916	0.006551	0.065261	0.00962
-0.8	1	13.9341	0.000144	0.055771	0.052766	0.01876	0.001077	0.043758	0.011153
-0.8	2	13.81651	0.07924	0.087824	0.05811	0.019222	0.004358	0.04213	0.012302
-0.8	3	14.67073	0.082479	0.064766	0.04761	0.016807	0.004245	0.050062	0.010591
-0.8	4	14.49372	0.140194	0.089191	0.05356	0.016175	0.006308	0.046756	0.011883
-0.8	5	14.90827	0.083976	0.061682	0.045129	0.016527	0.003991	0.055988	0.009921
-0.8	6	13.64836	0.079268	0.091364	0.060742	0.019364	0.004917	0.039458	0.012694
-0.8	7	15.50439	0.168256	0.07887	0.043593	0.012382	0.007051	0.058803	0.01001
-0.8	8	15.06681	0.000134	0.034887	0.040782	0.016234	0.000774	0.062492	0.009068
0.6	1	15.13447	7.24E-05	0.290931	0.260483	0.071909	0.00729	0.045758	0.011633
0.6	2	15.20314	0.102882	0.350039	0.292208	0.075922	0.016711	0.043237	0.012636
0.6	3	15.5592	0.113142	0.344549	0.250732	0.066945	0.014686	0.051913	0.011255
0.6	4	15.47707	0.215675	0.402438	0.279029	0.066892	0.023566	0.04911	0.012434
0.6	5	15.66995	0.100136	0.302089	0.242135	0.061703	0.01479	0.058968	0.01076
0.6	6	15.12592	0.115822	0.393547	0.301413	0.081289	0.016758	0.038959	0.012781
0.6	7	16.0475	0.236784	0.393931	0.231296	0.060557	0.021394	0.059235	0.010703
0.6	8	15.62007	0.000104	0.248085	0.21304	0.058076	0.006049	0.066321	0.009822
-0.6	1	13.84207	8.14E-05	0.097839	0.091469	0.032167	0.002447	0.044254	0.011199
-0.6	2	13.88897	0.082453	0.139715	0.10259	0.033444	0.006835	0.042944	0.012298
-0.6	3	14.45657	0.087932	0.115093	0.084569	0.029557	0.006366	0.050514	0.010635
-0.6	4	14.40633	0.16222	0.13229	0.09532	0.026554	0.009952	0.047565	0.011867
-0.6	5	14.55423	0.086021	0.104659	0.08206	0.027898	0.005655	0.05628	0.009903
-0.6	6	13.83787	0.088865	0.154204	0.1055	0.035239	0.007185	0.040396	0.012675
-0.6	7	15.14527	0.183664	0.134423	0.071238	0.021347	0.009382	0.059443	0.010052
-0.6	8	14.52769	0.000101	0.067553	0.07255	0.026907	0.002051	0.062611	0.008995

Table 4.47: Output currents with unbalance controller at 700V

Power Factor	Grid Conditions	I_f	I_{3f}	I_{5f}	I_{7f}	I_{11f}	I_{13f}	$I_{f_{sw}}$	$I_{f_{2sw}}$
1	1	14.39091	0.000116	0.084336	0.07031	0.025813	0.008783	0.03131	0.011322
1	2	14.10046	0.076783	0.099256	0.079448	0.028447	0.012615	0.035423	0.011047
1	3	15.22448	0.080184	0.096747	0.074079	0.026983	0.010898	0.034118	0.011945
1	4	14.86758	0.137844	0.10618	0.081632	0.028686	0.015206	0.036946	0.011784
1	5	15.63532	0.085684	0.100382	0.070302	0.024223	0.010927	0.036391	0.011892
1	6	13.77504	0.071828	0.098041	0.082833	0.031842	0.012697	0.041501	0.010625
1	7	16.16923	0.165133	0.105337	0.076665	0.029665	0.011971	0.038714	0.012096
1	8	15.97991	0.000145	0.083818	0.061458	0.021521	0.007525	0.040104	0.01174
0.8	1	15.05013	0.000105	0.284205	0.269796	0.077229	0.009695	0.029462	0.011118
0.8	2	14.98533	0.116092	0.349104	0.30199	0.08248	0.018988	0.032372	0.010747
0.8	3	15.62101	0.120828	0.34151	0.261716	0.072074	0.01817	0.0326	0.01184
0.8	4	15.40086	0.24631	0.404928	0.290419	0.071275	0.027051	0.033956	0.011558
0.8	5	15.87096	0.111097	0.307486	0.251507	0.06728	0.016749	0.036314	0.011923
0.8	6	14.79125	0.122448	0.382996	0.312687	0.087643	0.020605	0.037664	0.010245
0.8	7	16.27308	0.253678	0.395066	0.243718	0.065345	0.025273	0.037018	0.012093
0.8	8	15.98036	0.000116	0.247566	0.221629	0.062588	0.008268	0.04143	0.011922
-0.8	1	13.91308	8.52E-05	0.108451	0.079588	0.025597	0.002197	0.034089	0.011503
-0.8	2	13.80949	0.094324	0.152921	0.088825	0.026345	0.006641	0.038337	0.011293
-0.8	3	14.65668	0.097606	0.113932	0.073582	0.023684	0.005748	0.03664	0.012035
-0.8	4	14.47331	0.162971	0.148164	0.083172	0.021989	0.008826	0.040216	0.011953
-0.8	5	14.89831	0.098091	0.110748	0.069836	0.022708	0.006273	0.037969	0.011881
-0.8	6	13.63474	0.096052	0.161084	0.093031	0.026943	0.005743	0.044617	0.010866
-0.8	7	15.49436	0.198606	0.124234	0.064414	0.018555	0.008171	0.041626	0.012089
-0.8	8	15.04253	0.00014	0.072659	0.062386	0.022111	0.002309	0.04098	0.011609
0.6	1	15.14684	7.14E-05	0.348285	0.333943	0.091306	0.00776	0.029357	0.011039
0.6	2	15.23577	0.124143	0.426736	0.372594	0.097338	0.018204	0.031655	0.010656
0.6	3	15.57536	0.134798	0.421381	0.320658	0.08476	0.018293	0.032573	0.011781
0.6	4	15.47593	0.266944	0.498049	0.355508	0.084987	0.028298	0.033443	0.011478
0.6	5	15.69967	0.117523	0.369761	0.308309	0.078892	0.016551	0.036712	0.011899
0.6	6	15.14151	0.139806	0.479908	0.385918	0.103916	0.020544	0.036622	0.010144
0.6	7	16.06556	0.282738	0.490246	0.295981	0.073472	0.027923	0.037639	0.012023
0.6	8	15.6347	6.92E-05	0.298318	0.272452	0.073956	0.006771	0.042355	0.01198
-0.6	1	13.83494	8.97E-05	0.162244	0.127634	0.042493	0.002617	0.035413	0.011528
-0.6	2	13.89501	0.097151	0.218742	0.144172	0.044278	0.008499	0.039556	0.011358
-0.6	3	14.45782	0.102125	0.180684	0.119749	0.039878	0.00725	0.03784	0.012061
-0.6	4	14.39782	0.189761	0.203909	0.135387	0.03621	0.0121	0.04159	0.012028
-0.6	5	14.56173	0.100568	0.165574	0.115778	0.036967	0.007347	0.038917	0.011873
-0.6	6	13.83436	0.104185	0.239147	0.148752	0.047215	0.008267	0.045834	0.010936
-0.6	7	15.15191	0.213602	0.200812	0.10308	0.030333	0.011102	0.042974	0.012154
-0.6	8	14.52021	0.000113	0.115562	0.101729	0.035576	0.002187	0.04177	0.011545

Table 4.48: Output currents with unbalance controller at 600V

Power Factor	Grid Conditions	I_f	I_{3f}	I_{5f}	I_{7f}	I_{11f}	I_{13f}	$I_{f_{sw}}$	$I_{f_{2sw}}$
1	1	14.47815	0.000123	0.098353	0.086061	0.035063	0.012783	0.050208	0.006651
1	2	14.20197	0.08901	0.115835	0.095879	0.038545	0.017663	0.061033	0.005947
1	3	15.31834	0.091444	0.115175	0.090715	0.036479	0.015657	0.050879	0.008549
1	4	14.94238	0.155241	0.13357	0.099167	0.038233	0.020935	0.062324	0.007744
1	5	15.7465	0.098246	0.110796	0.08607	0.033273	0.015298	0.042553	0.009508
1	6	14.31036	1.424099	1.221436	0.957849	0.379992	0.225346	0.07207	0.005248
1	7	16.27257	0.186972	0.129019	0.094729	0.038931	0.017056	0.053117	0.010136
1	8	16.07654	0.000147	0.093074	0.076394	0.029673	0.011069	0.034653	0.010351
0.8	1	15.08644	0.000104	0.346672	0.358474	0.102096	0.011805	0.045677	0.006132
0.8	2	15.04369	0.154658	0.436776	0.398432	0.108906	0.022006	0.055892	0.005475
0.8	3	15.66014	0.15011	0.427384	0.347057	0.095399	0.023481	0.045894	0.008057
0.8	4	15.4158	0.316842	0.515663	0.383387	0.096919	0.033842	0.056746	0.007265
0.8	5	15.93355	0.144885	0.386661	0.331769	0.089309	0.019536	0.037981	0.009072
0.8	6	15.53173	2.047285	1.964666	1.358604	0.332339	0.208035	0.066723	0.004829
0.8	7	16.31305	0.312134	0.505217	0.323874	0.082034	0.033986	0.047305	0.009703
0.8	8	16.02399	0.000113	0.303346	0.294564	0.082992	0.010392	0.031143	0.009989
-0.8	1	13.93433	0.000112	0.195963	0.122585	0.036056	0.004848	0.05335	0.007088
-0.8	2	13.84396	0.118981	0.258749	0.13817	0.037326	0.010399	0.064047	0.006333
-0.8	3	14.68398	0.121699	0.200415	0.115361	0.034149	0.009739	0.054339	0.008949
-0.8	4	14.4919	0.199014	0.245072	0.131084	0.031771	0.013681	0.065998	0.008139
-0.8	5	14.93856	0.119987	0.191943	0.109101	0.03239	0.009732	0.046024	0.009858
-0.8	6	14.06853	0.770082	0.65343	0.734179	0.339254	0.236271	0.075205	0.005605
-0.8	7	15.53259	0.24654	0.209024	0.103061	0.028396	0.012076	0.057148	0.010482
-0.8	8	15.06499	0.000168	0.137529	0.096255	0.031285	0.004983	0.03834	0.010657
0.6	1	15.16741	8.86E-05	0.437495	0.450474	0.119705	0.009482	0.04423	0.005992
0.6	2	15.27785	0.174422	0.547475	0.496396	0.132027	0.021378	0.054203	0.00534
0.6	3	15.60193	0.169822	0.541995	0.431261	0.114258	0.023285	0.044317	0.007923
0.6	4	15.47534	0.356033	0.649876	0.46998	0.120355	0.032613	0.054972	0.007135
0.6	5	15.74758	0.156968	0.475578	0.412148	0.106708	0.018711	0.036659	0.008934
0.6	6	16.06023	2.187974	2.192771	1.47731	0.300402	0.240381	0.064914	0.004686
0.6	7	16.09278	0.355896	0.643124	0.398835	0.098731	0.037499	0.045464	0.009566
0.6	8	15.66219	0.00015	0.374731	0.367037	0.097364	0.00807	0.030452	0.009885
-0.6	1	13.84926	6.52E-05	0.266291	0.184014	0.058378	0.005035	0.054479	0.00726
-0.6	2	13.92715	0.123427	0.344537	0.20949	0.061212	0.013796	0.065051	0.006487
-0.6	3	14.47773	0.127265	0.285962	0.174768	0.055829	0.011379	0.05556	0.00909
-0.6	4	14.41165	0.231849	0.318305	0.198785	0.051406	0.016821	0.067251	0.008284
-0.6	5	14.59627	0.123355	0.263653	0.168179	0.051208	0.012248	0.047324	0.009944
-0.6	6	14.16437	0.529368	0.466073	0.655185	0.306528	0.215498	0.076213	0.005748
-0.6	7	15.18258	0.260784	0.306261	0.15322	0.044626	0.013669	0.058538	0.010567
-0.6	8	14.53265	0.000118	0.194315	0.146464	0.048963	0.004488	0.039913	0.01073

Table 4.49: Current THD with film DC-Link capacitor and unbalance controller at grid condition 1

DC-Link	Power Factor				
Voltage	-0.6	-0.8	1	0.8	0.6
900	0.84	0.608	0.869	1.922	2.253
800	1.074	0.687	0.82	2.219	2.658
700	1.564	1.04	0.837	2.678	3.265
600	2.423	1.736	1.017	3.406	4.246

Table 4.50: Current THD with film DC-Link capacitor and unbalance controller at grid condition 2

DC-Link	Power Factor				
Voltage	-0.6	-0.8	1	0.8	0.6
900	1.09	0.834	1.049	2.222	2.571
800	1.414	1.03	1.04	2.604	3.066
700	2.026	1.493	1.11	3.1814	3.814
600	3.036	2.33	1.334	4.104	5.031

Table 4.51: Current THD with film DC-Link capacitor and unbalance controller at grid condition 3

DC-Link	Power Factor				
Voltage	-0.6	-0.8	1	0.8	0.6
900	1.03	0.792	0.951	2.022	2.38
800	1.246	0.839	0.94	2.335	2.812
700	1.695	1.128	0.997	2.822	3.463
600	2.492	1.744	1.203	3.598	4.52

Table 4.52: Current THD with film DC-Link capacitor and unbalance controller at grid condition 4

DC-Link	Power Factor				
Voltage	-0.6	-0.8	1	0.8	0.6
900	1.343	1.135	1.237	2.457	2.282
800	1.541	1.236	1.249	2.874	3.365
700	1.944	1.514	1.319	3.513	4.192
600	2.787	2.227	1.543	4.542	5.555

Table 4.53: Current THD with film DC-Link capacitor and unbalance controller at grid condition 5

DC-Link Voltage	Power Factor				
	-0.6	**-0.8**	**1**	**0.8**	**0.6**
900	0.991	0.816	0.992	1.86	2.165
800	1.17	0.882	0.971	2.145	2.552
700	1.575	1.149	1.082	2.601	3.152
600	2.307	1.716	1.154	3.341	4.139

Table 4.54: Current THD with film DC-Link capacitor and unbalance controller at grid condition 6

DC-Link Voltage	Power Factor				
	-0.6	**-0.8**	**1**	**0.8**	**0.6**
900	1.179	0.816	1.037	2.4	2.798
800	1.552	1.032	1.041	2.801	3.329
700	2.204	1.536	1.148	3.408	4.13
600	8.673	10.951	16.292	22.13	23.57

Table 4.55: Current THD with film DC-Link capacitor and unbalance controller at grid condition 7

DC-Link Voltage	Power Factor				
	-0.6	**-0.8**	**1**	**0.8**	**0.6**
900	1.439	1.216	1.186	2.27	2.668
800	1.665	1.309	1.202	2.628	3.152
700	2.096	1.531	1.28	3.175	3.886
600	2.861	2.018	1.552	4.053	5.085

Table 4.56: Current THD with film DC-Link capacitor and unbalance controller at grid condition 8

DC-Link Voltage	Power Factor				
	-0.6	**-0.8**	**1**	**0.8**	**0.6**
900	0.773	0.637	0.814	1.589	1.881
800	0.86	0.729	0.754	1.8	2.184
700	1.149	0.736	0.735	2.146	2.656
600	1.746	1.178	0.82	2.712	3.429

4.3 DC-Link Capacitor Current and Lifetime Expectations

Capacitor ripple current is a very important parameter to calculate the lifetime of the capacitors. In a DC/AC converter, because of the switching operations and grid unbalanced condition, a ripple current flows on DC-Link capacitors. This ripple current includes low order even and odd harmonic current. There are also high-frequency ripple currents flow on DC-Link capacitors as switching frequency and its order, f_{sw}, f_{2sw}. e.g.

The ripple current has more importance for electrolytic capacitors than film capacitors. Because the ripple current capacity of the electrolytic capacitor is lower than the film capacitor. Film capacitor has great immunity to the ripple current. Therefore, only the electrolytic capacitor ripple current capacitor and lifetime expectations are investigated in this study.

The electrolytic capacitor - TDK-B43544A6477M0 is chosen as the DC-Link capacitor for this study because of the operating rated voltage and current ripple capability at 105 °C internal capacitor temperature. Furthermore The L_0 is 3000 H and I_0 is 2.52 A at 105 °C for TDK B43544A6477M0 [67].

The DC-Link capacitor current, $I_{DC-Link}$, is observed to validate the effects of the operating conditions on the DC-Link capacitor lifetime.

4.3.1 Current Ripple on DC-Link Capacitors

The current ripples at different operating conditions are obtained from simulations. In Table 4.57 - Table 4.60, DC-Link current ripples are given with respect to the DC-Link voltage without unbalance controller implementation. Then rated ripple current is calculated with (28). Rated ripple currents without unbalance controller are given in Table 4.61 - Table 4.68. Furthermore, the 3D form of rated ripple currents are given in Figure 4.34 - Figure 4.41.

Then the unbalance controller is activated, and the DC-Link capacitor ripple currents in Table 4.69 - Table 4.72 are obtained. Rated ripple currents without unbalance controller are given in Table 4.72 - Table 4.79. Furthermore, the 3D form of rated ripple currents are given in Figure 4.42 - Figure 4.49.

The injected compensation current that injected to the grid currents provides to eliminate second order harmonic current that flows on the DC-Link capacitor. According to Table 4.57 - Table 4.60 and Table 4.69 - Table 4.72, the second order harmonic component of DC-Link current decreases after the activation of the unbalance controller.

The some of low order harmonic terms of DC-Link ripple currents might decrease with the implementation of unbalance controller but the real important term to calculate lifetime of a capacitor is rated ripple current flows on capacitor. Therefore if Table 4.61 - Table 4.68 and Table 4.72 - Table 4.79 are observed, there is no significant change in rated ripple current.

Table 4.57: DC-link ripple currents without unbalance controller at 900V

Power Factor	Grid Conditions	$I_{DC-Link_f}$	$I_{DC-Link_{2f}}$	$I_{DC-Link_{3f}}$	$I_{DC-Link_{4f}}$	$I_{DC-Link_{5f}}$	$I_{DC-Link_{6f}}$	$I_{DC-Link_{7f}}$	$I_{DC-Link_{8f}}$	$I_{DC-Link_{9f}}$	$I_{DC-Link_{10f}}$	$I_{DC-Link_{f_{sw}}}$	$I_{DC-Link_{f_{2sw}}}$
1	1	4.51E-05	1.1E-05	0.633239	2.89E-05	4.95E-05	0.055578	4.96E-05	4.38E-05	0.345155	4.69E-05	12.19669	3.341363
1	2	0.027733	0.215388	0.641835	0.006032	0.049922	0.058632	0.051599	0.004557	0.342692	0.004941	11.6284	3.67186
1	3	0.024646	0.230647	0.633375	0.002954	0.057777	0.051369	0.048724	0.004718	0.336283	0.00396	12.7337	3.023231
1	4	0.041073	0.388574	0.645179	0.008365	0.094557	0.053826	0.086989	0.007914	0.328356	0.008481	12.1537	3.398882
1	5	0.030807	0.239312	0.629843	0.00585	0.052784	0.048057	0.055819	0.004156	0.333377	0.004467	13.28088	2.697277
1	6	0.023449	0.208601	0.646961	0.003383	0.054427	0.062272	0.045732	0.005151	0.34628	0.004307	11.07258	3.935629
1	7	0.043642	0.47872	0.644152	0.00375	0.122719	0.046264	0.09146	0.010296	0.313971	0.007106	13.23283	2.814875
1	8	5.91E-05	4.21E-06	0.621819	2.13E-05	5.13E-05	0.045415	4.75E-05	3.17E-05	0.337281	2.66E-05	13.83996	2.376781
0.8	1	2.71E-05	9.69E-05	2.79829	9.69E-05	6.92E-05	0.061038	8.25E-05	7.45E-05	0.336285	9.64E-05	9.572807	4.28143
0.8	2	0.151511	0.257603	2.885449	0.00743	0.110745	0.064202	0.049918	0.005066	0.334363	0.005749	9.148858	4.523332
0.8	3	0.15596	0.264769	2.700756	0.00412	0.109682	0.056515	0.052975	0.004972	0.327274	0.004867	9.973616	4.017334
0.8	4	0.273334	0.455667	2.780602	0.012114	0.199983	0.05903	0.076813	0.007959	0.321887	0.01028	9.5391	4.296397
0.8	5	0.153274	0.268798	2.609512	0.007219	0.110348	0.052889	0.053776	0.004591	0.3234	0.00509	10.38298	3.735197
0.8	6	0.153474	0.254854	2.979088	0.004665	0.109771	0.068198	0.050322	0.005589	0.337831	0.005344	8.735416	4.717893
0.8	7	0.317019	0.537928	2.591289	0.005492	0.216057	0.050777	0.107471	0.01066	0.305333	0.008846	10.3452	3.781434
0.8	8	3.66E-05	1.24E-05	2.525229	1.12E-05	7.18E-05	0.050078	7.12E-05	1.85E-05	0.326205	2.87E-05	10.80062	3.439948
-0.8	1	4.56E-05	6.93E-05	1.763148	4.04E-05	6E-05	0.057968	4.41E-05	0.000112	0.420025	4.39E-05	10.09277	3.732888
-0.8	2	0.135821	0.17364	1.813875	0.006695	0.049002	0.061262	0.06356	0.004625	0.424289	0.004272	9.661137	3.991579
-0.8	3	0.140924	0.187052	1.70589	0.004514	0.048369	0.053574	0.064134	0.004907	0.399341	0.003101	10.50621	3.479542
-0.8	4	0.232553	0.314485	1.754946	0.008035	0.073041	0.056087	0.117258	0.008639	0.394072	0.00695	10.06769	3.763674
-0.8	5	0.134289	0.194514	1.650403	0.006355	0.052607	0.049987	0.064043	0.004292	0.387446	0.003894	10.92595	3.222951
-0.8	6	0.1426	0.167588	1.867334	0.005042	0.044912	0.06523	0.06388	0.005223	0.437247	0.003524	9.237578	4.206311
-0.8	7	0.285289	0.388683	1.64459	0.007963	0.096438	0.048103	0.125487	0.010474	0.362283	0.005555	10.8958	3.296365
-0.8	8	6.8E-05	1.03E-05	1.597757	3.02E-05	6.59E-05	0.047181	5.09E-05	2.35E-05	0.384929	6.45E-05	11.35299	2.973928
0.6	1	2.09E-05	0.000104	3.442326	9.62E-05	5.44E-05	0.064336	6.34E-05	0.000107	0.34677	0.000107	7.505324	4.692902
0.6	2	0.192872	0.264353	3.552239	0.008255	0.127247	0.067587	0.050281	0.005279	0.347165	0.00611	7.214689	4.898865
0.6	3	0.19873	0.267842	3.318138	0.005148	0.123589	0.059501	0.05647	0.005177	0.335167	0.005139	7.783373	4.452368
0.6	4	0.344798	0.46445	3.419136	0.014313	0.225805	0.062179	0.081051	0.00817	0.331381	0.01081	7.48617	4.690089
0.6	5	0.19396	0.269573	3.201782	0.007942	0.12637	0.055727	0.052751	0.004745	0.32842	0.00538	8.066264	4.190853
0.6	6	0.196783	0.263478	3.670483	0.005618	0.124584	0.071794	0.05445	0.005791	0.353306	0.005737	6.930819	5.065974
0.6	7	0.403878	0.539822	3.177925	0.007654	0.240166	0.053444	0.117957	0.010836	0.310343	0.009518	8.043153	4.211676
0.6	8	1.84E-05	1.45E-05	3.094411	1.73E-05	7.28E-05	0.052752	8.37E-05	7.74E-06	0.328702	1.25E-05	8.352213	3.912354
-0.6	1	5.91E-05	8.92E-05	2.521356	5.72E-05	5.83E-05	0.060415	3.17E-05	0.000145	0.468877	2.13E-05	8.204653	4.230831
-0.6	2	0.185275	0.168461	2.595234	0.007304	0.069558	0.063864	0.071946	0.004819	0.475947	0.003923	7.89577	4.453895
-0.6	3	0.192719	0.177994	2.435963	0.005808	0.063373	0.055819	0.074863	0.005048	0.442304	0.002635	8.506441	3.998051
-0.6	4	0.32257	0.302107	2.505532	0.008431	0.107821	0.058354	0.133113	0.009059	0.438443	0.006244	8.194154	4.243511
-0.6	5	0.183733	0.183473	2.354784	0.006866	0.072284	0.051997	0.070797	0.00444	0.425827	0.003564	8.811723	3.754321
-0.6	6	0.194068	0.163819	2.67441	0.006342	0.061258	0.0681	0.075617	0.005327	0.493354	0.003198	7.591851	4.642029
-0.6	7	0.391246	0.365984	2.340677	0.011176	0.119954	0.050035	0.148954	0.01057	0.397056	0.004829	8.796055	3.800122
-0.6	8	7.44E-05	9.44E-06	2.27945	4.29E-05	6.55E-05	0.049058	4.82E-05	2.57E-05	0.420415	6.67E-05	9.120234	3.506873

Table 4.58: DC-link ripple currents without unbalance controller at 800V

Power Factor	Grid Conditions	$I_{DC-Link_f}$	$I_{DC-Link_{2f}}$	$I_{DC-Link_{3f}}$	$I_{DC-Link_{4f}}$	$I_{DC-Link_{5f}}$	$I_{DC-Link_{6f}}$	$I_{DC-Link_{7f}}$	$I_{DC-Link_{8f}}$	$I_{DC-Link_{9f}}$	$I_{DC-Link_{10f}}$	$I_{DC-Link_{f_{sw}}}$	$I_{DC-Link_{f_{2sw}}}$
1	1	5.08E-05	1.66E-05	0.695302	1.61E-05	5.02E-05	0.062433	6.33E-05	4.61E-05	0.380912	4.04E-05	10.93554	4.654295
1	2	0.030973	0.23665	0.704636	0.006927	0.055314	0.066116	0.056734	0.00514	0.378231	0.00563	10.22044	4.776556
1	3	0.027569	0.252902	0.69554	0.0031	0.063952	0.057619	0.053583	0.005333	0.370915	0.00448	11.62312	4.421609
1	4	0.0458	0.426574	0.70847	0.010878	0.104709	0.06055	0.095791	0.00886	0.362193	0.009707	10.89239	4.623222
1	5	0.034326	0.26189	0.691717	0.006557	0.058452	0.053807	0.061395	0.004696	0.367653	0.005053	12.32375	4.117005
1	6	0.026295	0.230017	0.710042	0.004093	0.060291	0.07067	0.050239	0.00582	0.381993	0.005001	9.522535	4.819296
1	7	0.048888	0.524388	0.70752	0.002921	0.135739	0.051797	0.10053	0.011603	0.346298	0.008073	12.27148	4.12729
1	8	4.94E-05	9.83E-06	0.682877	2.18E-06	4.69E-05	0.05078	5.08E-05	2.96E-05	0.37188	2.44E-05	13.04179	3.710152
0.8	1	6E-05	0.000173	3.125177	0.000179	4.59E-05	0.06961	4.28E-05	0.000159	0.376677	0.000175	8.662882	5.186439
0.8	2	0.169475	0.286732	3.222429	0.008551	0.123974	0.073376	0.056441	0.005982	0.374434	0.006766	8.125239	5.24105
0.8	3	0.174388	0.294415	3.016417	0.004528	0.122909	0.064371	0.059704	0.005669	0.366589	0.005855	9.182905	5.029759
0.8	4	0.305733	0.506737	3.105456	0.014937	0.224126	0.067318	0.086995	0.009074	0.360291	0.012202	8.626685	5.148293
0.8	5	0.17142	0.298611	2.914497	0.008283	0.12356	0.060169	0.060655	0.005415	0.362236	0.005882	9.71723	4.815726
0.8	6	0.17162	0.283989	3.32685	0.005554	0.12301	0.078241	0.056762	0.006488	0.378196	0.006431	7.608856	5.229832
0.8	7	0.354553	0.597852	2.894322	0.006225	0.24218	0.057721	0.120971	0.012271	0.341845	0.010378	9.673279	4.802276
0.8	8	1.07E-05	0.000105	3.101605	0.0001	4.64E-05	0.058439	5.2E-05	9.65E-05	0.388945	0.000112	10.38649	4.83415
-0.8	1	4.2E-05	0.000165	1.983356	0.000127	2.54E-05	0.066411	4.33E-05	0.000194	0.473449	8.57E-05	9.353526	4.755918
-0.8	2	0.152972	0.195472	2.04049	0.008284	0.055361	0.070443	0.071366	0.005204	0.478251	0.004749	8.796893	4.868358
-0.8	3	0.158712	0.210186	1.91882	0.005312	0.054569	0.061244	0.072064	0.00562	0.450204	0.003283	9.899534	4.549661
-0.8	4	0.261709	0.353905	1.9741	0.010898	0.082629	0.064235	0.131914	0.009882	0.444305	0.007588	9.331535	4.724433
-0.8	5	0.151216	0.218047	1.856362	0.007557	0.059415	0.057057	0.071873	0.004805	0.436823	0.004357	10.45506	4.286734
-0.8	6	0.160548	0.189237	2.100737	0.0063	0.050649	0.07533	0.071789	0.005905	0.492863	0.003888	8.254761	4.914883
-0.8	7	0.321195	0.436332	1.849765	0.008498	0.108646	0.054882	0.14107	0.011863	0.408593	0.005988	10.42353	4.291582
-0.8	8	5.84E-05	8.51E-05	1.797074	5.7E-05	6E-05	0.05377	5.34E-05	0.000107	0.433955	3.5E-05	11.02259	3.952238
0.6	1	4.91E-05	0.000229	3.872748	0.000214	3.49E-05	0.074206	9.67E-06	0.000234	0.391562	0.00023	6.836073	5.394338
0.6	2	0.217408	0.295427	3.996249	0.009584	0.14331	0.078113	0.057203	0.006228	0.391965	0.007391	6.471115	5.424115
0.6	3	0.224046	0.299135	3.733144	0.006039	0.139191	0.068547	0.064112	0.006009	0.378378	0.006257	7.197727	5.269159
0.6	4	0.388636	0.518731	3.846779	0.017702	0.254617	0.071763	0.092283	0.00945	0.373911	0.012963	6.815323	5.352989
0.6	5	0.21868	0.30097	3.602466	0.009194	0.142254	0.064238	0.060038	0.005525	0.3708	0.006434	7.572743	5.093644
0.6	6	0.221837	0.29464	4.129041	0.006856	0.140355	0.083229	0.061831	0.006764	0.39871	0.007021	6.128101	5.396328
0.6	7	0.455148	0.602852	3.575658	0.009161	0.270834	0.061526	0.133512	0.01252	0.350131	0.011435	7.544268	5.07104
0.6	8	6.1E-06	0.000127	3.481711	0.000135	6.71E-05	0.06078	7.47E-05	0.000117	0.371172	0.000125	7.959413	4.861129
-0.6	1	4.45E-05	0.000209	2.8365	0.000171	9.34E-06	0.070176	2.79E-05	0.000258	0.528007	0.000136	7.584238	4.997448
-0.6	2	0.208547	0.18782	2.919664	0.009224	0.07853	0.074369	0.080936	0.005507	0.536071	0.004292	7.196111	5.084913
-0.6	3	0.216942	0.198311	2.740342	0.007131	0.071323	0.064648	0.084349	0.00585	0.497952	0.002666	7.977773	4.824893
-0.6	4	0.36309	0.337042	2.818535	0.011487	0.12184	0.067731	0.15001	0.010533	0.493625	0.006548	7.57982	4.963824
-0.6	5	0.20682	0.20408	2.649008	0.008389	0.081486	0.06018	0.079613	0.005084	0.47932	0.003857	8.378709	4.605974
-0.6	6	0.218385	0.182845	3.008809	0.007928	0.069059	0.079668	0.085251	0.005975	0.555816	0.003516	6.821402	5.117929
-0.6	7	0.440554	0.407407	2.632969	0.012979	0.134633	0.057921	0.16795	0.012036	0.44691	0.005017	8.364835	4.601606
-0.6	8	4.95E-05	9.95E-05	2.564325	6.28E-05	5.84E-05	0.056684	3.78E-05	0.000144	0.473177	4.42E-05	8.787795	4.333229

Table 4.59: DC-link ripple currents without unbalance controller at 700V

Power Factor	Grid Conditions	$I_{DC-Link_f}$	$I_{DC-Link_{2f}}$	$I_{DC-Link_{3f}}$	$I_{DC-Link_{4f}}$	$I_{DC-Link_{5f}}$	$I_{DC-Link_{6f}}$	$I_{DC-Link_{7f}}$	$I_{DC-Link_{8f}}$	$I_{DC-Link_{9f}}$	$I_{DC-Link_{10f}}$	$I_{DC-Link_{f_{sw}}}$	$I_{DC-Link_{f_{2sw}}}$
1	1	5.68E-05	2.18E-05	0.793297	3.17E-05	5.61E-05	0.073074	6.56E-05	2.51E-05	0.436241	1.66E-05	8.905692	5.288928
1	2	0.036116	0.273235	0.803237	0.008876	0.063671	0.078349	0.064568	0.005924	0.432973	0.006628	8.006275	4.972562
1	3	0.032178	0.290668	0.79432	0.004176	0.073564	0.066857	0.061066	0.006147	0.42501	0.005263	9.805923	5.435909
1	4	0.053599	0.491207	0.808536	0.015869	0.120433	0.07099	0.109344	0.010142	0.414851	0.011467	8.884627	5.193273
1	5	0.040034	0.300111	0.790557	0.007789	0.067352	0.061947	0.070072	0.005411	0.421423	0.005885	10.72277	5.496306
1	6	0.03065	0.266897	0.808493	0.006708	0.069247	0.084908	0.05709	0.006721	0.43702	0.005972	7.13345	4.601158
1	7	0.057096	0.601703	0.808782	0.00421	0.156105	0.059677	0.114623	0.013338	0.397104	0.009522	10.68147	5.405036
1	8	5.86E-05	3.37E-06	0.780877	1.39E-05	5.81E-05	0.058096	6.94E-05	3.56E-05	0.426388	8.94E-06	11.6665	5.450249
0.8	1	0.000114	0.000247	3.57094	0.000228	5.83E-05	0.082818	1.27E-05	0.000247	0.432847	0.00023	7.096509	5.321065
0.8	2	0.194301	0.32778	3.681549	0.010376	0.141871	0.088142	0.065621	0.007132	0.429965	0.008416	6.47963	4.990121
0.8	3	0.199842	0.335986	3.447156	0.005693	0.140875	0.076079	0.069143	0.006639	0.421339	0.007446	7.73737	5.510887
0.8	4	0.350433	0.57841	3.548482	0.019876	0.25692	0.080297	0.101494	0.010511	0.41359	0.015201	7.078241	5.243664
0.8	5	0.196488	0.340341	3.331024	0.009795	0.141479	0.070714	0.070414	0.006547	0.416376	0.007163	8.409543	5.626584
0.8	6	0.196742	0.325346	3.800277	0.007778	0.140843	0.095047	0.065844	0.00761	0.434066	0.008235	5.918571	4.608395
0.8	7	0.40643	0.681773	3.30827	0.00864	0.277724	0.067905	0.139933	0.014418	0.392673	0.012982	8.373891	5.543624
0.8	8	7.27E-05	0.000214	3.223849	0.000197	3.3E-05	0.06667	9.17E-06	0.000198	0.420254	0.000209	9.117236	5.65413
-0.8	1	4.48E-05	0.000221	2.266773	0.000226	3.45E-05	0.079224	5.57E-05	0.000223	0.542336	0.000184	7.81235	5.203521
-0.8	2	0.175007	0.22521	2.332203	0.011296	0.06362	0.084746	0.081221	0.006121	0.547817	0.005305	7.143357	4.944659
-0.8	3	0.181625	0.241208	2.192838	0.007049	0.062533	0.072505	0.082225	0.006611	0.515823	0.003523	8.510251	5.311094
-0.8	4	0.299258	0.407133	2.256095	0.016351	0.095063	0.076647	0.150733	0.011678	0.509066	0.008349	7.815439	5.120581
-0.8	5	0.172999	0.249276	2.121328	0.009662	0.068204	0.067193	0.081854	0.005541	0.500477	0.004889	9.226529	5.340458
-0.8	6	0.1837	0.219159	2.40135	0.009374	0.058053	0.091636	0.081932	0.006878	0.564582	0.004286	6.509643	4.631974
-0.8	7	0.367483	0.499827	2.113669	0.010025	0.124216	0.064629	0.161094	0.013717	0.468343	0.006534	9.210305	5.260574
-0.8	8	6.23E-05	0.000184	2.05348	0.000178	4.2E-05	0.06298	6.82E-05	0.000215	0.497162	0.000139	9.966324	5.27916
0.6	1	9.29E-05	0.000313	4.450483	0.000288	4.21E-05	0.089391	7.18E-05	0.000321	0.45208	0.000296	5.780819	5.307066
0.6	2	0.25064	0.337382	4.591976	0.011907	0.164665	0.094843	0.066817	0.007611	0.452269	0.009292	5.433691	4.989594
0.6	3	0.258229	0.341327	4.290469	0.007708	0.160101	0.082156	0.074503	0.007174	0.43678	0.008091	6.178771	5.500267
0.6	4	0.447847	0.591801	4.420745	0.023345	0.293158	0.086673	0.10781	0.011114	0.431238	0.016433	5.777668	5.241846
0.6	5	0.252152	0.343179	4.140726	0.011057	0.163453	0.076693	0.070056	0.006704	0.428196	0.008075	6.617972	5.625094
0.6	6	0.255721	0.336962	4.744038	0.009508	0.161417	0.101997	0.071909	0.008104	0.459906	0.009092	5.156541	4.622631
0.6	7	0.524589	0.687941	4.109838	0.012399	0.311781	0.073414	0.154727	0.014828	0.403921	0.014745	6.598295	5.550957
0.6	8	9.35E-05	0.000264	4.002198	0.000261	3.3E-05	0.072331	1.14E-05	0.000255	0.42873	0.000255	7.096445	5.673796
-0.6	1	6.06E-05	0.000298	3.218663	0.000296	3.55E-05	0.084925	4.92E-05	0.000301	0.630065	0.000253	7.716938	5.737507
-0.6	2	0.237987	0.242933	3.314533	0.01305	0.090629	0.090653	0.095597	0.006491	0.638345	0.004776	7.136698	5.473058
-0.6	3	0.247149	0.257614	3.108407	0.009074	0.083734	0.07781	0.099166	0.006968	0.596284	0.002817	8.347893	5.84494
-0.6	4	0.411578	0.437323	3.19919	0.017636	0.139201	0.081968	0.178532	0.012663	0.589819	0.007047	7.734363	5.652342
-0.6	5	0.236457	0.232053	3.026363	0.011079	0.093452	0.07208	0.091034	0.006083	0.549274	0.004131	7.468499	5.339222
-0.6	6	0.249762	0.209399	3.43812	0.011489	0.079038	0.098027	0.097979	0.007097	0.637407	0.00362	5.710364	4.685038
-0.6	7	0.503916	0.463803	3.007845	0.016261	0.153621	0.069386	0.192844	0.014084	0.5121	0.0051	7.472954	5.267391
-0.6	8	7.27E-05	0.000258	2.92969	0.000228	4.17E-05	0.067652	9.05E-05	0.000308	0.542264	0.000209	7.987798	5.29581

Table 4.60: DC-link ripple currents without unbalance controller at 600V

Power Factor	Grid Conditions	$I_{DC-Link_f}$	$I_{DC-Link_{2f}}$	$I_{DC-Link_{3f}}$	$I_{DC-Link_{4f}}$	$I_{DC-Link_{5f}}$	$I_{DC-Link_{6f}}$	$I_{DC-Link_{7f}}$	$I_{DC-Link_{8f}}$	$I_{DC-Link_{9f}}$	$I_{DC-Link_{10f}}$	$I_{DC-Link_{f_{sw}}}$	$I_{DC-Link_{f_{2sw}}}$
1	1	7.06E-05	2.63E-05	0.918567	4.72E-05	8.3E-05	0.094951	0.000105	2.6E-05	0.508012	6.24E-05	5.270115	3.63614
1	2	0.042899	0.326526	0.928566	0.01383	0.074511	0.104842	0.074481	0.007005	0.50373	0.008181	4.322601	2.965696
1	3	0.038338	0.344402	0.921252	0.008604	0.086074	0.084836	0.070646	0.007287	0.495429	0.00638	6.368159	4.349526
1	4	0.063899	0.584149	0.936484	0.026725	0.140794	0.092667	0.126792	0.011838	0.483167	0.014092	5.37154	3.671231
1	5	0.047644	0.35349	0.918137	0.010567	0.078989	0.07687	0.081244	0.00638	0.491623	0.007114	7.490894	5.000523
1	6	0.078348	1.716917	1.070377	2.283293	0.0205	1.701132	0.028985	1.218972	0.510264	0.682343	3.695694	2.522723
1	7	0.06818	0.710375	0.93948	0.012926	0.182676	0.074308	0.132755	0.015768	0.46349	0.011621	7.528239	4.940369
1	8	7.48E-05	2.5E-05	0.907853	2.58E-05	6.67E-05	0.070576	8.3E-05	3.16E-05	0.497735	3.52E-05	8.661017	5.61245
0.8	1	3.77E-05	0.000103	4.163333	6.49E-05	0.000122	0.108657	0.000135	8.72E-05	0.507424	4.19E-05	5.000414	3.448446
0.8	2	0.227687	0.385997	4.291369	0.014349	0.16547	0.118745	0.07813	0.008682	0.503219	0.011311	4.693973	2.887804
0.8	3	0.234135	0.394086	4.020089	0.009577	0.164534	0.098	0.082262	0.00817	0.494173	0.00988	5.525513	4.099832
0.8	4	0.41029	0.679243	4.137446	0.030022	0.300525	0.106175	0.121439	0.01228	0.48415	0.020196	5.073124	3.506773
0.8	5	0.230213	0.398101	3.885634	0.012475	0.165148	0.089539	0.083886	0.00816	0.488822	0.009296	6.164737	4.711477
0.8	6	0.095508	2.956154	4.627242	3.53915	0.146213	2.526883	0.049051	1.558885	0.543363	0.792259	4.993153	2.694458
0.8	7	0.475905	0.798466	3.859064	0.016151	0.325167	0.086387	0.165824	0.017368	0.460346	0.017534	6.196277	4.672339
0.8	8	7.29E-05	0.000238	3.761253	0.000196	4.6E-05	0.083042	2.74E-05	0.000225	0.493824	0.00022	6.915485	5.292745
-0.8	1	4.09E-05	0.000108	2.645582	0.000143	4.08E-05	0.103007	9.21E-05	8.9E-05	0.634062	0.000151	5.335252	3.727529
-0.8	2	0.204321	0.269022	2.722264	0.017745	0.074782	0.112488	0.094041	0.007777	0.640428	0.005789	4.825295	3.145635
-0.8	3	0.212208	0.285458	2.558767	0.011685	0.072993	0.09257	0.095731	0.007948	0.603094	0.003861	6.053932	4.334348
-0.8	4	0.349463	0.484322	2.632624	0.027809	0.111874	0.099826	0.175554	0.01433	0.595118	0.00922	5.437656	3.75432
-0.8	5	0.202153	0.293244	2.475055	0.014039	0.080064	0.084476	0.094845	0.006826	0.585211	0.005388	6.84067	4.881401
-0.8	6	0.231358	0.895606	2.757483	1.316839	0.105945	1.00538	0.063759	0.835069	0.632096	0.540768	4.50364	2.741199
-0.8	7	0.429439	0.589665	2.465842	0.016897	0.144481	0.081337	0.187759	0.016486	0.547887	0.00691	6.899957	4.819167
-0.8	8	0.000101	0.00021	2.395757	0.000239	4.4E-05	0.078119	3.01E-05	0.000238	0.581361	0.000228	7.696855	5.384013
0.6	1	4.39E-05	0.000111	5.163755	7.15E-05	0.000109	0.117454	6.91E-05	0.000126	0.526671	8.65E-05	4.987692	3.385447
0.6	2	0.291712	0.386343	5.327074	0.023489	0.191309	0.125504	0.079219	0.015171	0.525493	0.013923	5.062559	2.900764
0.6	3	0.300455	0.396357	4.97912	0.011733	0.186375	0.106341	0.087674	0.00889	0.509275	0.011058	5.09966	3.972304
0.6	4	0.52095	0.687019	5.12942	0.033845	0.341549	0.11453	0.127719	0.013131	0.501821	0.022407	5.047727	3.451632
0.6	5	0.293454	0.397624	4.805892	0.014408	0.189909	0.097827	0.082957	0.008701	0.499593	0.010546	5.335635	4.527426
0.6	6	0.142775	3.279704	5.712749	3.854252	0.202687	2.790039	0.069006	1.562778	0.563036	0.859801	5.688465	2.850021
0.6	7	0.610485	0.797786	4.770544	0.020327	0.363409	0.094026	0.181604	0.018171	0.470814	0.019984	5.374673	4.499525
0.6	8	9.4E-05	0.000285	4.645677	0.000261	2.79E-05	0.091084	5.02E-05	0.000284	0.500803	0.000273	5.701269	5.052622
-0.6	1	1.55E-05	0.000153	3.779367	0.000182	9.74E-05	0.111493	7.5E-05	0.000137	0.710432	0.000207	5.214646	3.756732
-0.6	2	0.27841	0.253929	3.890523	0.019955	0.105762	0.120989	0.108864	0.008551	0.721296	0.004845	5.089384	3.246212
-0.6	3	0.28974	0.265986	3.650537	0.014653	0.095418	0.10061	0.113871	0.00841	0.669738	0.002958	5.551391	4.291381
-0.6	4	0.484468	0.455179	3.754829	0.028951	0.164945	0.107809	0.202476	0.015905	0.663905	0.006927	5.313076	3.784288
-0.6	5	0.276075	0.272183	3.528396	0.016223	0.109544	0.092118	0.106622	0.007686	0.644546	0.004424	5.977275	4.774008
-0.6	6	0.297544	0.658374	3.971939	0.964511	0.132216	0.731239	0.086367	0.663024	0.716865	0.455836	5.102054	2.875732
-0.6	7	0.588394	0.545249	3.506514	0.024383	0.179087	0.088648	0.226867	0.017128	0.600843	0.005007	6.052203	4.715044
-0.6	8	8.83E-05	0.000297	3.415497	0.000311	1.59E-05	0.085553	5.4E-05	0.000316	0.636267	0.000301	6.490852	5.210744

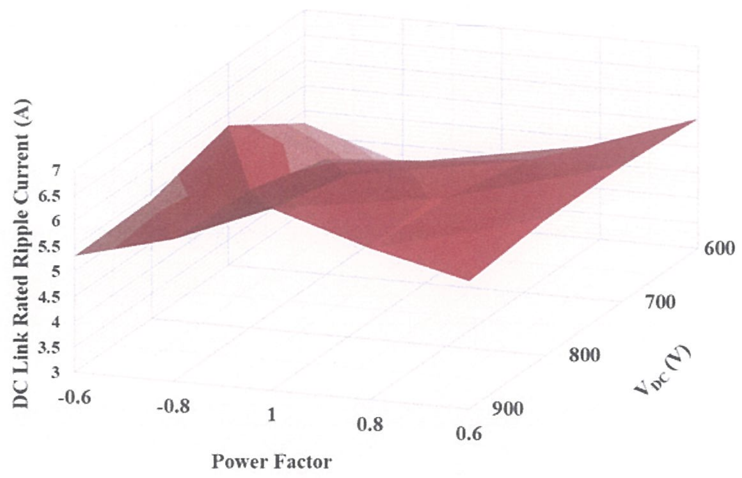

Figure 4.34: DC-link rated ripple currents without unbalance controller at grid condition 1

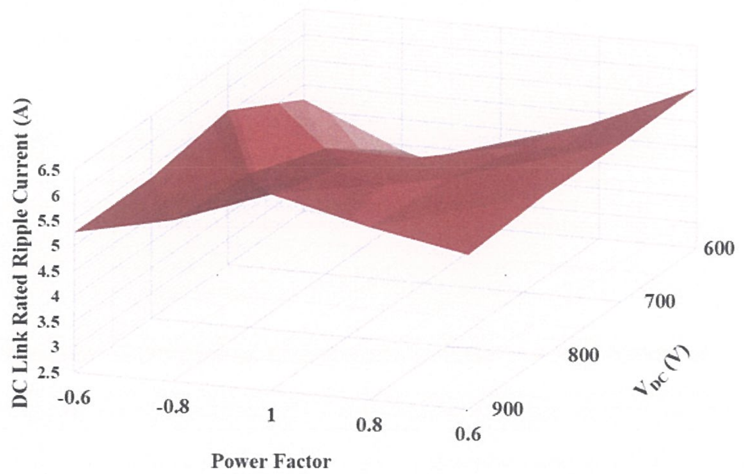

Figure 4.35: DC-link rated ripple currents without unbalance controller at grid condition 2

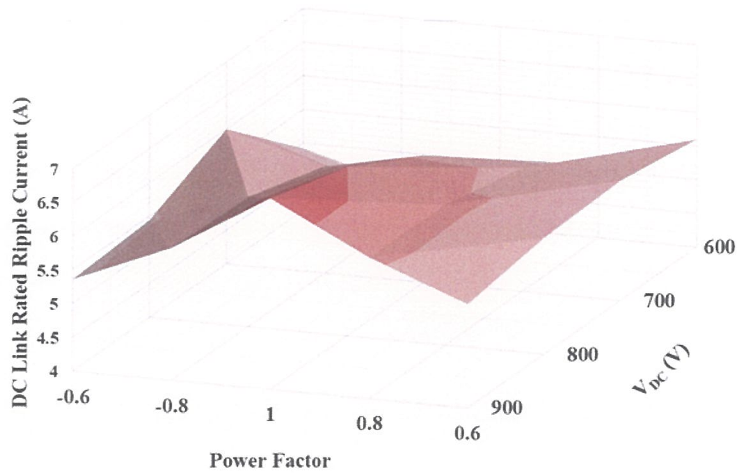

Figure 4.36: DC-link rated ripple currents without unbalance controller at grid condition 3

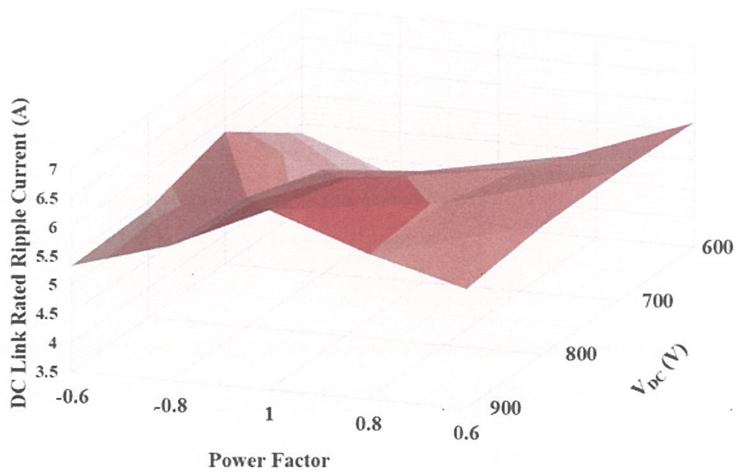

Figure 4.37: DC-link rated ripple currents without unbalance controller at grid condition 4

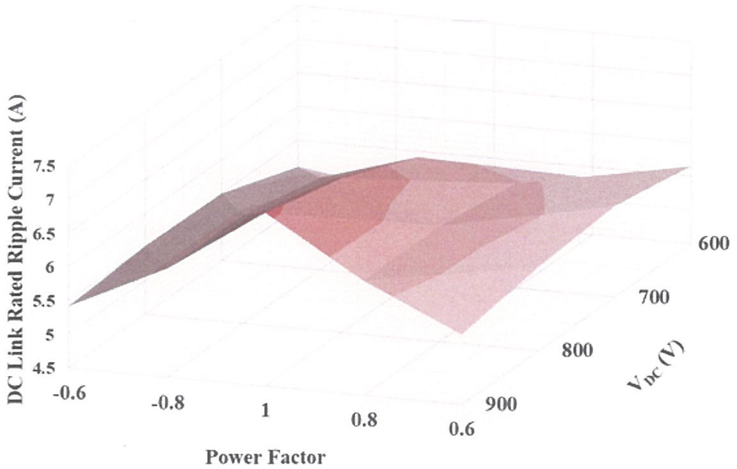

Figure 4.38: DC-link rated ripple currents without unbalance controller at grid condition 5

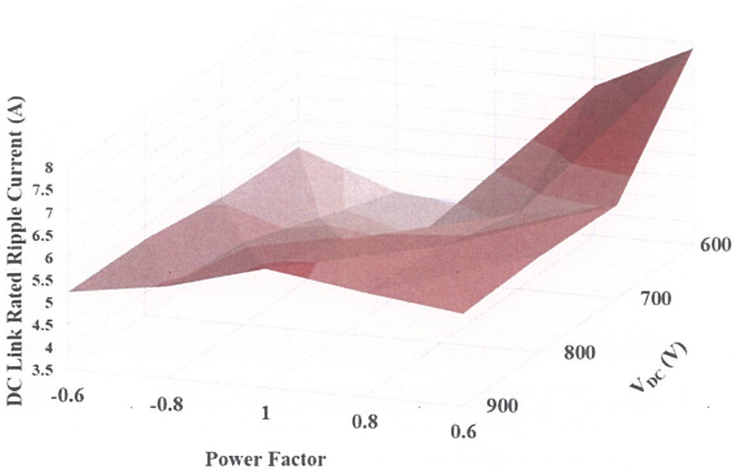

Figure 4.39: DC-link rated ripple currents without unbalance controller at grid condition 6

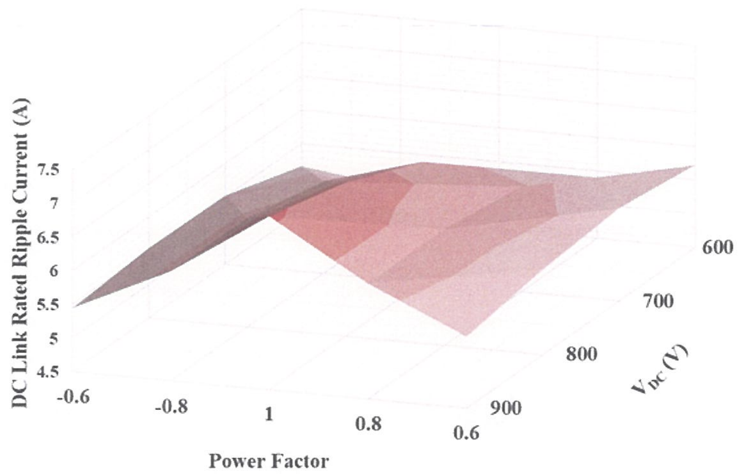

Figure 4.40: DC-link rated ripple currents without unbalance controller at grid condition 7

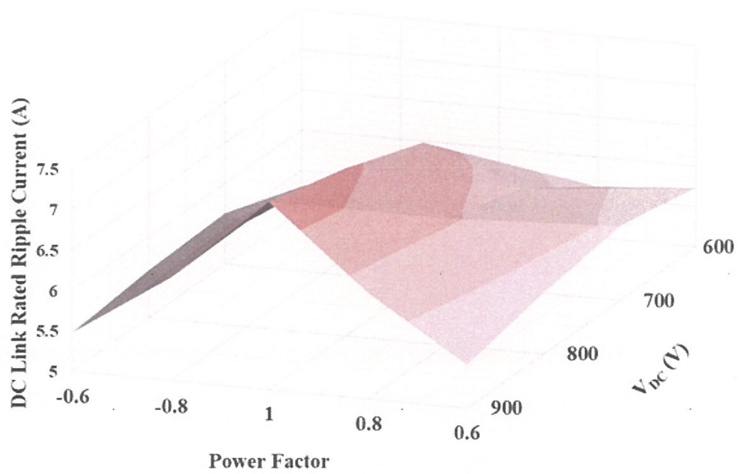

Figure 4.41: DC-link rated ripple currents without unbalance controller at grid condition 8

Table 4.61: DC-link rated ripple currents without unbalance controller at grid condition 1

DC-Link	Power Factor				
Voltage	-0.6	-0.8	1	0.8	0.6
900	5.303383	5.813616	6.599126	5.993969	5.52899
800	5.361974	5.738819	6.211492	5.941675	5.691291
700	5.77265	5.289321	5.435754	5.603468	5.689076
600	4.759966	4.14035	3.442322	4.875507	5.567853

Table 4.62: DC-link rated ripple currents without unbalance controller at grid condition 2

DC-Link	Power Factor				
Voltage	-0.6	-0.8	1	0.8	0.6
900	5.263211	5.678576	6.37001	5.904678	5.540833
800	5.285827	5.546663	5.905915	5.800857	5.667235
700	5.555426	4.991654	4.965566	5.388516	5.628865
600	4.715586	3.8918	2.886136	4.808497	5.661909

Table 4.63: DC-link rated ripple currents without unbalance controller at grid condition 3

DC-Link	Power Factor				
Voltage	-0.6	-0.8	1	0.8	0.6
900	5.359745	5.95926	6.831618	6.094693	5.532397
800	5.444021	5.927737	6.501232	6.082404	5.722509
700	6.000722	5.586264	5.882932	5.833155	5.775201
600	4.923974	4.524012	4.118668	5.091858	5.596544

Table 4.64: DC-link rated ripple currents without unbalance controller at grid condition 4

DC-Link	Power Factor				
Voltage	-0.6	-0.8	1	0.8	0.6
900	5.321813	5.821936	6.59849	6.005793	5.550661
800	5.376789	5.740999	6.201219	5.947893	5.70993
700	5.790314	5.295629	5.426505	5.618328	5.719078
600	4.844785	4.229626	3.548672	4.971041	5.65818

Table 4.65: DC-link rated ripple currents without unbalance controller at grid condition 5

DC-Link Voltage	Power Factor				
	-0.6	-0.8	1	0.8	0.6
900	5.415451	6.109496	7.071854	6.198509	5.532103
800	5.518062	6.113251	6.789245	6.218929	5.743589
700	5.503081	5.871055	6.314217	6.056474	5.851547
600	5.102507	4.921592	4.775896	5.343901	5.648908

Table 4.66: DC-link rated ripple currents without unbalance controller at grid condition 6

DC-Link Voltage	Power Factor				
	-0.6	-0.8	1	0.8	0.6
900	5.218577	5.54272	6.141277	5.81282	5.544825
800	5.200469	5.347654	5.59234	5.653843	5.632698
700	4.940384	4.694845	4.487044	5.183866	5.573903
600	4.86512	4.073945	3.862005	6.841267	7.884211

Table 4.67: DC-link rated ripple currents without unbalance controller at grid condition 7

DC-Link Voltage	Power Factor				
	-0.6	-0.8	1	0.8	0.6
900	5.441109	6.122694	7.073469	6.212809	5.558065
800	5.540869	6.121318	6.782345	6.227119	5.765377
700	5.524524	5.874296	6.298105	6.062192	5.874523
600	5.168009	4.975736	4.819011	5.405972	5.720178

Table 4.68: DC-link rated ripple currents without unbalance controller at grid condition 8

DC-Link Voltage	Power Factor				
	-0.6	-0.8	1	0.8	0.6
900	5.473556	6.266512	7.321005	6.306786	5.529889
800	5.586789	6.297186	7.075936	6.565269	5.755205
700	5.630944	6.146667	6.732756	6.273999	5.918068
600	5.300752	5.33881	5.432987	5.635535	5.72973

Table 4.69: DC-link ripple currents with unbalance controller at 900V

Power Factor	Grid Conditions	$I_{DC-Link_f}$	$I_{DC-Link_{2f}}$	$I_{DC-Link_{3f}}$	$I_{DC-Link_{4f}}$	$I_{DC-Link_{5f}}$	$I_{DC-Link_{6f}}$	$I_{DC-Link_{7f}}$	$I_{DC-Link_{8f}}$	$I_{DC-Link_{9f}}$	$I_{DC-Link_{10f}}$	$I_{DC-Link_{f_{sw}}}$	$I_{DC-Link_{f_{2sw}}}$
1	1	0.000129	1.15E-05	0.633356	4.21E-05	0.000138	0.053623	0.000124	2.91E-05	0.348469	5.72E-05	12.19694	3.340435
1	2	0.070951	0.078933	0.644998	0.008378	0.073248	0.056309	0.045848	0.002898	0.347662	0.005685	11.6381	3.666495
1	3	0.066332	0.08443	0.636869	0.007746	0.081363	0.050044	0.039938	0.003486	0.341216	0.005011	12.74362	3.016263
1	4	0.122099	0.142745	0.656258	0.014315	0.131187	0.051975	0.078966	0.005713	0.335048	0.00936	12.18257	3.38259
1	5	0.078969	0.087827	0.633922	0.007818	0.080646	0.047102	0.049298	0.002631	0.337784	0.005124	13.29054	2.692027
1	6	0.060371	0.076532	0.649911	0.008372	0.074222	0.059458	0.037992	0.003815	0.351132	0.005518	11.08208	3.931078
1	7	0.125198	0.175536	0.660355	0.015317	0.169401	0.045017	0.070879	0.008345	0.322743	0.009546	13.27272	2.793353
1	8	0.000196	1.34E-05	0.62212	2.42E-05	0.000194	0.044718	0.000166	3.05E-05	0.340037	3.22E-05	13.84023	2.375971
0.8	1	8.21E-05	9.26E-05	2.793211	6.75E-05	0.000106	0.060302	0.000139	7.67E-05	0.328876	0.000101	9.569932	4.280882
0.8	2	0.192698	0.09103	2.884444	0.01017	0.088417	0.063028	0.04714	0.003589	0.327368	0.005572	9.153089	4.524753
0.8	3	0.200832	0.093177	2.700362	0.009558	0.088891	0.056134	0.04757	0.003961	0.321981	0.004883	9.978041	4.019946
0.8	4	0.355005	0.161317	2.788534	0.018064	0.161297	0.058162	0.07177	0.006339	0.317746	0.009349	9.557823	4.303234
0.8	5	0.195072	0.094475	2.60945	0.009537	0.091203	0.052754	0.050877	0.003313	0.318556	0.004996	10.38735	3.739052
0.8	6	0.197297	0.090411	2.977096	0.01044	0.086144	0.066626	0.045053	0.004434	0.330001	0.0052	8.739383	4.71901
0.8	7	0.411744	0.189518	2.605818	0.019067	0.177251	0.050369	0.093547	0.009104	0.305068	0.009164	10.37182	3.797579
0.8	8	0.00011	1.64E-05	2.521642	1.93E-05	9.95E-05	0.050199	0.000126	1.57E-05	0.320787	3.52E-05	10.79844	3.439944
-0.8	1	0.000161	7.13E-05	1.764802	6.32E-05	0.000181	0.055706	9.97E-05	0.00012	0.423987	2.91E-05	10.09584	3.730622
-0.8	2	0.156407	0.068904	1.818008	0.009103	0.06681	0.058595	0.06463	0.0029	0.428911	0.005464	9.669765	3.989441
-0.8	3	0.160441	0.073501	1.710328	0.008704	0.068414	0.051775	0.063498	0.00355	0.403985	0.00464	10.51477	3.478375
-0.8	4	0.260454	0.124307	1.763843	0.01526	0.105102	0.053849	0.12034	0.006223	0.398986	0.008669	10.08764	3.762644
-0.8	5	0.157599	0.07641	1.655184	0.008391	0.072909	0.048546	0.06452	0.002622	0.391576	0.004887	10.93407	3.223985
-0.8	6	0.160472	0.066629	1.870916	0.009406	0.063027	0.06201	0.06365	0.003776	0.441785	0.005338	9.246394	4.203859
-0.8	7	0.323449	0.152147	1.658021	0.017281	0.137873	0.046434	0.12262	0.008345	0.368195	0.008932	10.92252	3.299263
-0.8	8	0.000136	1.06E-05	1.599128	3.04E-05	0.000206	0.045966	0.00014	3.36E-05	0.38836	6.94E-05	11.35518	2.973029
0.6	1	9.37E-05	0.000112	3.436963	8.56E-05	6.68E-05	0.064065	0.000113	0.000118	0.336047	0.000103	7.501514	4.691641
0.6	2	0.236443	0.092974	3.552333	0.011178	0.092997	0.066861	0.050803	0.003889	0.336397	0.005497	7.214875	4.903949
0.6	3	0.246656	0.093812	3.318273	0.010712	0.089295	0.059531	0.054327	0.004233	0.326199	0.004679	7.783193	4.458615
0.6	4	0.429742	0.163642	3.428741	0.02016	0.165839	0.0618	0.08189	0.006824	0.323065	0.009135	7.493189	4.707433
0.6	5	0.237311	0.094075	3.202133	0.010377	0.093823	0.05605	0.053542	0.003497	0.320181	0.004966	8.065859	4.19808
0.6	6	0.244061	0.093285	3.666313	0.011527	0.088734	0.070686	0.052046	0.004675	0.341178	0.005135	6.930127	5.066353
0.6	7	0.506047	0.189362	3.194897	0.021238	0.173286	0.053389	0.110274	0.009451	0.305906	0.008909	8.05385	4.243566
0.6	8	8.08E-05	1.93E-05	3.090649	1.79E-05	0.000115	0.053233	0.000137	4.89E-05	0.320621	3.21E-05	8.349184	3.911917
-0.6	1	0.000124	8.76E-05	2.522135	7.04E-05	0.000139	0.058104	6.92E-05	0.000151	0.471245	5.02E-06	8.208449	4.229518
-0.6	2	0.210516	0.070674	2.598066	0.009922	0.069657	0.061182	0.076229	0.003077	0.478424	0.005237	7.902091	4.455292
-0.6	3	0.219067	0.073606	2.439861	0.009715	0.06529	0.053922	0.077296	0.00369	0.444894	0.004342	8.512512	4.001782
-0.6	4	0.361087	0.125852	2.514523	0.016621	0.10579	0.056069	0.140518	0.006629	0.440582	0.008189	8.205663	4.253989
-0.6	5	0.210645	0.075741	2.358795	0.009157	0.074152	0.050461	0.074879	0.002819	0.428123	0.004623	8.817257	3.759551
-0.6	6	0.219157	0.068864	2.676573	0.010464	0.061845	0.064906	0.078072	0.003891	0.495597	0.005145	7.598475	4.642642
-0.6	7	0.44612	0.150079	2.355066	0.019435	0.125696	0.048245	0.151845	0.008452	0.399977	0.008427	8.811074	3.81969
-0.6	8	6.88E-05	1.4E-05	2.280704	4.37E-05	0.000113	0.047718	4.54E-05	1.43E-05	0.422663	7.32E-05	9.123086	3.507256

Table 4.70: DC-link ripple currents with unbalance controller at 800V

Power Factor	Grid Conditions	$I_{DC-Link_f}$	$I_{DC-Link_{2f}}$	$I_{DC-Link_{3f}}$	$I_{DC-Link_{4f}}$	$I_{DC-Link_{5f}}$	$I_{DC-Link_{6f}}$	$I_{DC-Link_{7f}}$	$I_{DC-Link_{8f}}$	$I_{DC-Link_{9f}}$	$I_{DC-Link_{10f}}$	$I_{DC-Link_{f_{sw}}}$	$I_{DC-Link_{f_{2sw}}}$
1	1	0.000127	9.89E-06	0.695348	1.62E-05	0.000159	0.058641	0.000142	3.51E-05	0.383939	5.46E-05	10.93547	4.653753
1	2	0.078325	0.088803	0.707964	0.00925	0.080766	0.061534	0.050425	0.00326	0.382692	0.006387	10.23245	4.775218
1	3	0.073215	0.093894	0.699235	0.008494	0.08969	0.0546	0.043989	0.003893	0.375737	0.005588	11.63596	4.416932
1	4	0.13463	0.159594	0.720495	0.016208	0.144612	0.056703	0.087019	0.006329	0.368847	0.010519	10.93003	4.615894
1	5	0.087161	0.096997	0.696049	0.008592	0.08892	0.051423	0.054266	0.002942	0.371973	0.005722	12.33672	4.110252
1	6	0.066651	0.086939	0.71321	0.009324	0.081823	0.065146	0.041792	0.004267	0.386425	0.006211	9.534031	4.820172
1	7	0.138119	0.194423	0.725157	0.016826	0.186726	0.049079	0.078035	0.009324	0.355359	0.010676	12.3246	4.1043
1	8	0.000227	1.70E-05	0.683076	1.64E-05	0.000225	0.048878	0.000204	3.27E-05	0.374464	3.27E-05	13.04187	3.709438
0.8	1	9.40E-05	0.000191	3.119488	0.000173	0.000166	0.067231	0.000191	0.000175	0.366215	0.0002	8.659135	5.1862
0.8	2	0.215237	0.103269	3.220945	0.011609	0.098689	0.070232	0.052574	0.004224	0.364261	0.006192	8.132257	5.242055
0.8	3	0.224352	0.104954	3.016121	0.010793	0.099438	0.062593	0.052951	0.004457	0.358773	0.005493	9.190204	5.031517
0.8	4	0.3966	0.182162	3.11367	0.021065	0.180181	0.064785	0.080093	0.00721	0.353669	0.01043	8.655962	5.151366
0.8	5	0.217938	0.105938	2.914584	0.010842	0.101931	0.058806	0.056776	0.003842	0.355091	0.005519	9.724691	4.817178
0.8	6	0.220354	0.103154	3.324505	0.012023	0.096281	0.074482	0.05006	0.00511	0.366873	0.005746	7.615407	5.23134
0.8	7	0.459992	0.212731	2.910044	0.021907	0.198372	0.056134	0.104076	0.010365	0.340048	0.009971	9.714017	4.809105
0.8	8	0.000165	0.000104	3.097256	8.69E-05	8.53E-05	0.057584	0.000137	9.59E-05	0.379954	9.70E-05	10.38333	4.834509
-0.8	1	0.000131	0.000154	1.984039	0.000137	0.000218	0.062342	0.000155	0.00019	0.477164	6.62E-05	9.357848	4.752355
-0.8	2	0.175981	0.079195	2.043193	0.010455	0.075558	0.065662	0.072609	0.003216	0.482571	0.006164	8.808447	4.865609
-0.8	3	0.180514	0.083821	1.922582	0.010023	0.077356	0.057917	0.071403	0.004055	0.454781	0.0051	9.911124	4.546788
-0.8	4	0.292846	0.142507	1.982205	0.017934	0.118987	0.060185	0.135353	0.007057	0.449042	0.009667	9.358126	4.723471
-0.8	5	0.177382	0.086477	1.860518	0.00952	0.082483	0.054307	0.072471	0.002882	0.440894	0.005523	10.46624	4.283869
-0.8	6	0.180464	0.077305	2.103167	0.010919	0.071233	0.06964	0.071521	0.004258	0.496962	0.005983	8.266554	4.913101
-0.8	7	0.363783	0.172809	1.863773	0.019715	0.155777	0.051884	0.137944	0.009415	0.414655	0.009934	10.45983	4.288036
-0.8	8	0.000187	8.28E-05	1.797714	5.86E-05	0.000203	0.05144	0.000118	0.000103	0.437319	3.30E-05	11.02557	3.949182
0.6	1	0.000162	0.000236	3.866705	0.000198	4.16E-05	0.072506	8.61E-05	0.000237	0.377029	0.000219	6.831712	5.392935
0.6	2	0.26596	0.105594	3.99336	0.012956	0.104284	0.075586	0.056828	0.00453	0.376974	0.006193	6.474126	5.423592
0.6	3	0.277753	0.105886	3.733355	0.012487	0.100236	0.067316	0.060835	0.004856	0.366138	0.005189	7.200467	5.273157
0.6	4	0.483781	0.185181	3.857446	0.02402	0.186242	0.070073	0.091668	0.007907	0.36248	0.010158	6.833093	5.361929
0.6	5	0.267227	0.105876	3.602862	0.011991	0.105247	0.06352	0.06013	0.004008	0.359585	0.00556	7.575217	5.098022
0.6	6	0.274762	0.106467	4.124442	0.013557	0.099576	0.080258	0.05816	0.00542	0.382288	0.005678	6.13084	5.394372
0.6	7	0.569688	0.213361	3.594202	0.024819	0.194789	0.060345	0.123348	0.01074	0.343476	0.009831	7.567368	5.093253
0.6	8	9.57E-05	0.000148	3.477256	0.000119	0.000149	0.060322	0.000164	0.000142	0.360195	0.000141	7.955802	4.860676
-0.6	1	0.000169	0.000201	2.835255	0.000176	0.000135	0.066267	5.56E-05	0.000254	0.529606	0.000127	7.589684	4.993793
-0.6	2	0.236585	0.080139	2.920658	0.011685	0.078539	0.069782	0.085696	0.003509	0.53769	0.00589	7.20528	5.083375
-0.6	3	0.246217	0.083165	2.742658	0.011529	0.073364	0.061408	0.08705	0.004313	0.499964	0.004674	7.986319	4.825495
-0.6	4	0.405956	0.1428	2.826859	0.020046	0.11914	0.063823	0.15823	0.007701	0.495043	0.008998	7.596225	4.970904
-0.6	5	0.236761	0.085124	2.652073	0.010681	0.083462	0.057491	0.084189	0.003219	0.481094	0.005141	8.386689	4.608015
-0.6	6	0.246273	0.078397	3.009423	0.012359	0.069565	0.074278	0.087911	0.004345	0.557052	0.005816	6.831211	5.116638
-0.6	7	0.501618	0.169011	2.647572	0.022804	0.140934	0.05497	0.171179	0.009627	0.449409	0.009259	8.385651	4.616276
-0.6	8	7.24E-05	9.14E-05	2.56442	7.13E-05	0.00013	0.054335	7.56E-05	0.000132	0.475007	4.77E-05	8.791811	4.331322

Table 4.71: DC-link ripple currents with unbalance controller at 700V

Power Factor	Grid Conditions	$I_{DC-Link_f}$	$I_{DC-Link_{2f}}$	$I_{DC-Link_{3f}}$	$I_{DC-Link_{4f}}$	$I_{DC-Link_{5f}}$	$I_{DC-Link_{6f}}$	$I_{DC-Link_{7f}}$	$I_{DC-Link_{8f}}$	$I_{DC-Link_{9f}}$	$I_{DC-Link_{10f}}$	$I_{DC-Link_{f_{sw}}}$	$I_{DC-Link_{f_{2sw}}}$
1	1	0.000143	1.67E-05	0.793194	3.81E-05	0.000181	0.06563	0.000155	3.26E-05	0.438194	3.55E-05	8.904922	5.289238
1	2	0.090054	0.107663	0.806856	0.010643	0.092705	0.069672	0.057365	0.00369	0.436407	0.007347	8.020736	4.980085
1	3	0.084303	0.111764	0.798315	0.009602	0.102982	0.060638	0.050109	0.004414	0.429182	0.006378	9.82224	5.440415
1	4	0.15503	0.191478	0.821984	0.019323	0.166056	0.063562	0.099249	0.00712	0.420983	0.012086	8.932947	5.211139
1	5	0.100378	0.114216	0.795326	0.009565	0.102216	0.056804	0.0619	0.00336	0.425193	0.006526	10.74005	5.497456
1	6	0.076642	0.107111	0.811938	0.011228	0.093785	0.074849	0.047467	0.004846	0.440221	0.007161	7.146395	4.610102
1	7	0.159179	0.229659	0.828638	0.019043	0.214433	0.054215	0.088923	0.010571	0.406258	0.012197	10.75182	5.414604
1	8	0.000252	1.13E-05	0.780924	1.18E-05	0.000252	0.05384	0.000228	3.80E-05	0.428291	2.80E-05	11.66628	5.450223
0.8	1	7.41E-05	0.000239	3.564503	0.00021	0.000208	0.07778	0.000221	0.000243	0.417136	0.000253	7.091069	5.320751
0.8	2	0.246163	0.122658	3.679545	0.013774	0.112546	0.081985	0.060024	0.005009	0.4144	0.007101	6.490602	4.99288
0.8	3	0.256683	0.12316	3.44728	0.012701	0.113723	0.071965	0.060352	0.005117	0.409106	0.006312	7.748923	5.514851
0.8	4	0.453745	0.214721	3.558067	0.025718	0.205766	0.075087	0.091627	0.008342	0.402727	0.012003	7.123802	5.252845
0.8	5	0.249369	0.123464	3.330561	0.012649	0.116428	0.067269	0.064968	0.004597	0.40518	0.006227	8.421636	5.628891
0.8	6	0.252047	0.123733	3.797529	0.014583	0.109878	0.088083	0.056911	0.005913	0.416796	0.006646	5.92857	4.611141
0.8	7	0.526348	0.248415	3.326091	0.026144	0.227212	0.064328	0.118458	0.012016	0.388102	0.011109	8.435781	5.556528
0.8	8	0.000251	0.000231	3.21866	0.000205	5.72E-05	0.063921	0.000116	0.000218	0.408629	0.000222	9.113104	5.654637
-0.8	1	0.000142	0.000187	2.264258	0.000205	0.000238	0.071901	0.000175	0.000196	0.545101	0.000119	7.818702	5.198721
-0.8	2	0.201064	0.095191	2.332817	0.01277	0.086738	0.076298	0.082726	0.003757	0.551221	0.007042	7.15937	4.94474
-0.8	3	0.206237	0.099344	2.19461	0.012061	0.088744	0.06638	0.081549	0.004769	0.519856	0.005687	8.526201	5.310454
-0.8	4	0.33455	0.170275	2.263581	0.022333	0.136728	0.069403	0.154598	0.008266	0.51317	0.010987	7.850856	5.129403
-0.8	5	0.202644	0.101318	2.123758	0.011208	0.094729	0.062028	0.082609	0.003308	0.504089	0.006302	9.242262	5.338465
-0.8	6	0.206113	0.094348	2.401134	0.013746	0.081627	0.081798	0.081632	0.004935	0.567453	0.006801	6.525564	4.632957
-0.8	7	0.415372	0.203504	2.127244	0.023463	0.178614	0.059191	0.157606	0.010834	0.47412	0.011238	9.258794	5.26827
-0.8	8	0.00024	0.000171	2.052633	0.00017	0.000182	0.058601	7.89E-05	0.000198	0.500146	0.000135	9.970937	5.274566
0.6	1	0.000207	0.0003	4.443599	0.000268	6.92E-05	0.085485	0.000134	0.000297	0.431212	0.000286	5.775704	5.305248
0.6	2	0.305706	0.12454	4.58587	0.015781	0.119058	0.089858	0.064802	0.00545	0.43048	0.007159	5.441848	4.984732
0.6	3	0.319556	0.123703	4.290206	0.01516	0.114667	0.078916	0.069381	0.005685	0.419102	0.006	6.186765	5.50123
0.6	4	0.556354	0.217228	4.432427	0.029942	0.213035	0.082892	0.104616	0.00927	0.414482	0.011791	5.814947	5.243158
0.6	5	0.307454	0.123044	4.14063	0.01435	0.120344	0.074205	0.068819	0.0048	0.411959	0.006369	6.625685	5.626319
0.6	6	0.315976	0.126569	4.739156	0.016887	0.113929	0.096374	0.066034	0.006333	0.436292	0.006626	5.165084	4.618999
0.6	7	0.655462	0.248557	4.13129	0.030367	0.223357	0.07061	0.14044	0.012476	0.393495	0.011166	6.643975	5.563662
0.6	8	8.59E-05	0.000263	3.996598	0.000233	0.000199	0.070421	0.000199	0.000253	0.412912	0.000262	7.091874	5.67265
-0.6	1	1.58E-04	0.000246	3.214239	2.56E-04	2.44E-04	0.077926	0.000166	0.000263	0.63063	0.000174	7.726541	5.73133
-0.6	2	2.71E-01	0.105379	3.313105	1.47E-02	9.90E-02	0.082631	0.100028	0.004082	0.639133	0.006746	7.154428	5.470163
-0.6	3	2.80E-01	0.109262	3.108291	1.41E-02	9.55E-02	0.071991	0.101095	0.005125	0.597928	0.005204	8.364204	5.842773
-0.6	4	4.60E-01	0.188082	3.205854	2.54E-02	1.52E-01	0.075049	0.186466	0.009103	0.590834	0.010206	7.766609	5.657963
-0.6	5	0.270253	0.098846	3.027344	0.013091	0.095785	0.067324	0.096221	0.003898	0.54992	0.005758	7.481091	5.338198
-0.6	6	0.281146	0.093307	3.435787	0.015853	0.079663	0.089011	0.100778	0.005175	0.636601	0.006472	5.726253	4.682087
-0.6	7	0.572686	0.196821	3.022148	0.028051	0.161125	0.064382	0.196398	0.01129	0.513712	0.010204	7.503583	5.279202
-0.6	8	0.000114	0.000248	2.926622	0.000238	0.000218	0.063531	0.000183	0.000302	0.54306	0.000199	7.994042	5.29025

Table 4.72: DC-link ripple currents with unbalance controller at 600V

Power Factor	Grid Conditions	$I_{DC-Link_f}$	$I_{DC-Link_{2f}}$	$I_{DC-Link_{3f}}$	$I_{DC-Link_{4f}}$	$I_{DC-Link_{5f}}$	$I_{DC-Link_{6f}}$	$I_{DC-Link_{7f}}$	$I_{DC-Link_{8f}}$	$I_{DC-Link_{9f}}$	$I_{DC-Link_{10f}}$	$I_{DC-Link_{f_{sw}}}$	$I_{DC-Link_{f_{2sw}}}$
1	1	0.000186	2.44E-05	0.918071	3.47E-05	0.00019	0.081878	0.00017	2.86E-05	0.507479	7.64E-06	5.266663	3.636439
1	2	0.105006	0.140812	0.932398	0.014071	0.108018	0.090365	0.066119	0.00427	0.504599	0.008803	4.335508	2.977561
1	3	0.098655	0.141922	0.925556	0.012535	0.120166	0.073355	0.05794	0.005107	0.49777	0.007486	6.38564	4.364503
1	4	0.181072	0.246389	0.951589	0.026438	0.193629	0.079833	0.114919	0.008073	0.487507	0.01439	5.425154	3.71139
1	5	0.117503	0.14232	0.923269	0.011366	0.119464	0.066866	0.07175	0.003894	0.493814	0.007666	7.511696	5.015535
1	6	0.106425	1.81549	1.098276	2.078573	0.108894	1.617368	0.041339	1.231078	0.511777	0.766557	3.745296	2.535499
1	7	0.186533	0.287831	0.962092	0.02458	0.250371	0.064157	0.10296	0.012243	0.471855	0.014301	7.61216	4.996489
1	8	0.00029	2.01E-05	0.907518	1.22E-05	0.000282	0.061928	0.000259	4.09E-05	0.497957	5.85E-05	8.659517	5.613337
0.8	1	0.000157	9.25E-05	4.155304	5.99E-05	0.000179	0.100204	0.000206	7.53E-05	0.48228	9.01E-05	4.992278	3.445574
0.8	2	0.287371	0.155553	4.288918	0.017827	0.130512	0.109483	0.069612	0.006061	0.477868	0.008666	4.708356	2.890371
0.8	3	0.29982	0.153025	4.018532	0.01665	0.13238	0.090658	0.069938	0.006199	0.473905	0.007384	5.541551	4.104697
0.8	4	0.529779	0.269036	4.148709	0.034374	0.239274	0.09796	0.106515	0.00958	0.465509	0.014668	5.137584	3.524601
0.8	5	0.291319	0.151432	3.884757	0.015554	0.135462	0.083027	0.075763	0.005656	0.470368	0.007309	6.183023	4.718024
0.8	6	0.095227	3.055651	4.621749	3.293359	0.133666	2.456145	0.038189	1.601293	0.533792	0.919848	5.033922	2.628981
0.8	7	0.614788	0.30593	3.879492	0.033817	0.265375	0.080012	0.136966	0.014076	0.450347	0.013174	6.286128	4.699084
0.8	8	0.000297	0.00026	3.755114	0.000216	0.000127	0.077472	0.000178	0.000233	0.475157	0.000247	6.908836	5.2923
-0.8	1	0.000243	0.000104	2.637874	0.000143	0.000279	0.090369	0.000215	8.70E-05	0.634625	0.000109	5.3449	3.724498
-0.8	2	0.234092	0.123515	2.717432	0.017772	0.101349	0.098319	0.095846	0.004835	0.64133	0.00807	4.844938	3.14954
-0.8	3	0.240202	0.125321	2.555819	0.016213	0.103449	0.081576	0.094957	0.005662	0.60534	0.00663	6.075007	4.338254
-0.8	4	0.389658	0.21809	2.635837	0.031474	0.159759	0.087444	0.179879	0.009978	0.597181	0.012752	5.479934	3.771891
-0.8	5	0.236264	0.125615	2.474336	0.014519	0.110853	0.074966	0.095938	0.004101	0.58747	0.007251	6.863062	4.885441
-0.8	6	0.272097	0.949159	2.763501	1.162881	0.124077	0.930714	0.07579	0.821652	0.630516	0.591651	4.558984	2.74627
-0.8	7	0.484047	0.254099	2.477728	0.031364	0.208068	0.071587	0.18392	0.012962	0.552551	0.012825	6.960463	4.84826
-0.8	8	0.00032	0.000204	2.391423	0.000228	0.000211	0.069879	0.000113	0.000213	0.583103	0.0002	7.704805	5.379211
0.6	1	0.000205	0.000104	5.153697	5.97E-05	0.000151	0.111048	0.000193	9.15E-05	0.494887	0.000128	4.981466	3.381567
0.6	2	0.355044	0.152956	5.322713	0.023314	0.137188	0.120366	0.074073	0.007932	0.49319	0.006967	5.076331	2.898647
0.6	3	0.370983	0.151333	4.977833	0.020017	0.13282	0.100854	0.079091	0.006931	0.48218	0.007253	5.115848	3.969878
0.6	4	0.645949	0.267286	5.142048	0.040052	0.245973	0.108276	0.119606	0.010625	0.475674	0.015035	5.109857	3.452772
0.6	5	0.357062	0.14871	4.805519	0.018379	0.138988	0.093091	0.079115	0.006236	0.474841	0.007422	5.352673	4.52681
0.6	6	0.153561	3.383172	5.705401	3.610141	0.185949	2.744584	0.059843	1.61417	0.550054	1.000128	5.725883	2.745295
0.6	7	0.761328	0.301607	4.793907	0.040028	0.259241	0.089128	0.160191	0.014821	0.453704	0.013433	5.456104	4.502495
0.6	8	0.000111	0.000256	4.638377	0.00022	0.00022	0.086938	0.000216	0.000245	0.476745	0.000274	5.69527	5.050141
-0.6	1	0.000206	0.000157	3.76845	0.000188	0.000211	0.10012	0.000138	0.000148	0.707036	0.000198	5.228655	3.751798
-0.6	2	0.314419	0.119327	3.882282	0.020655	0.105776	0.108177	0.114623	0.005593	0.717426	0.007435	5.111131	3.243747
-0.6	3	0.327275	0.120313	3.645501	0.019343	0.09854	0.090739	0.116969	0.00622	0.667698	0.006015	5.573252	4.288146
-0.6	4	0.539041	0.210911	3.755392	0.036154	0.16104	0.096667	0.212117	0.01146	0.660368	0.01129	5.350932	3.784594
-0.6	5	0.31472	0.120941	3.524371	0.01737	0.112572	0.083655	0.112457	0.004993	0.642689	0.006556	5.998688	4.770805
-0.6	6	0.347429	0.672587	3.967435	0.836876	0.122018	0.665175	0.096369	0.64215	0.708764	0.491142	5.153272	2.872053
-0.6	7	0.666472	0.242257	3.517561	0.037984	0.188745	0.079908	0.230308	0.013741	0.600136	0.011376	6.098955	4.723278
-0.6	8	0.000196	0.000302	3.408312	0.000325	0.000283	0.078195	0.000219	0.000342	0.634977	0.000292	6.502483	5.20372

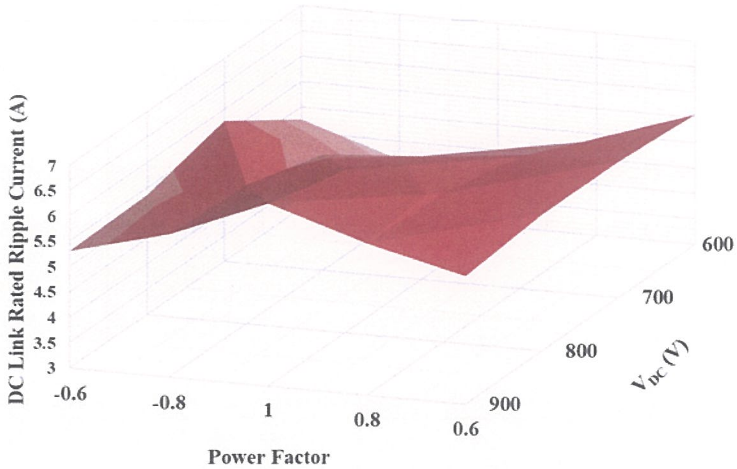

Figure 4.42: DC-link rated ripple currents with unbalance controller at grid condition 1.

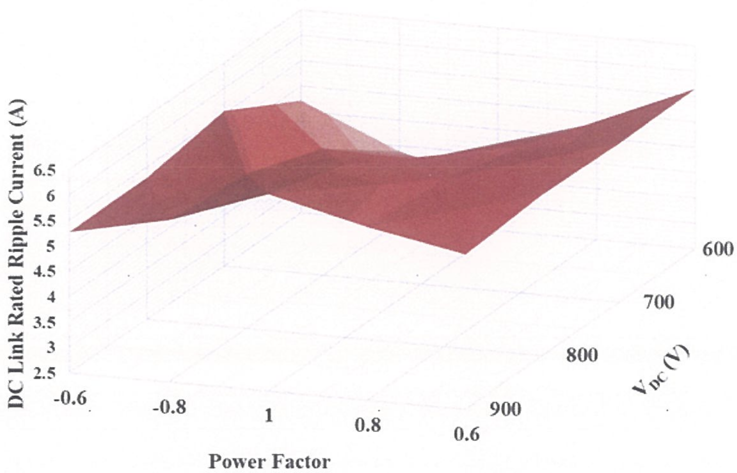

Figure 4.43: DC-link rated ripple currents with unbalance controller at grid condition 2.

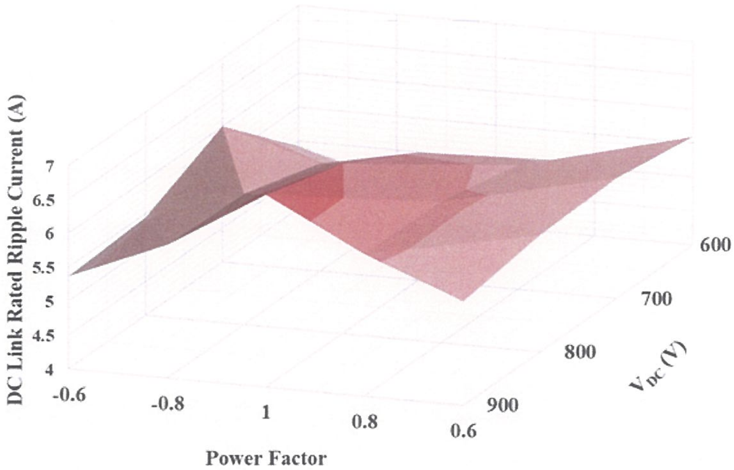

Figure 4.44: DC-link rated ripple currents with unbalance controller at grid condition 3.

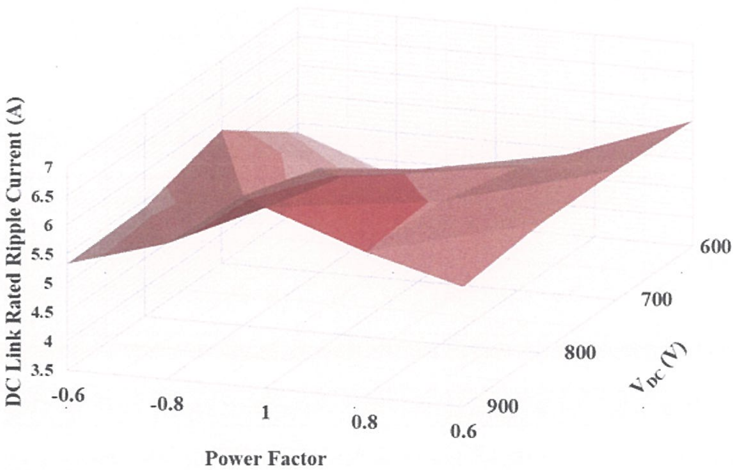

Figure 4.45: DC-link rated ripple currents with unbalance controller at grid condition 4.

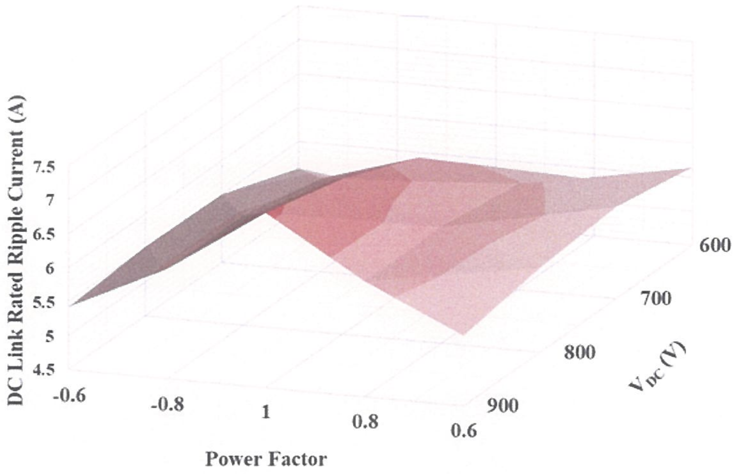

Figure 4.46: DC-link rated ripple currents with unbalance controller at grid condition 5.

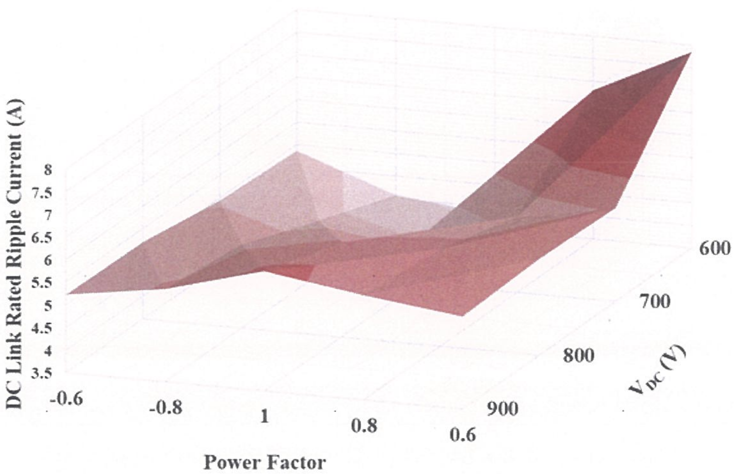

Figure 4.47: DC-link rated ripple currents with unbalance controller at grid condition 6.

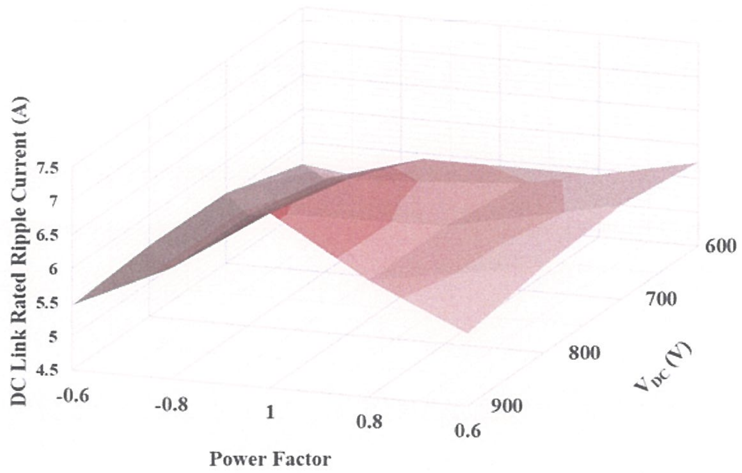

Figure 4.48: DC-link rated ripple currents with unbalance controller at grid condition 7.

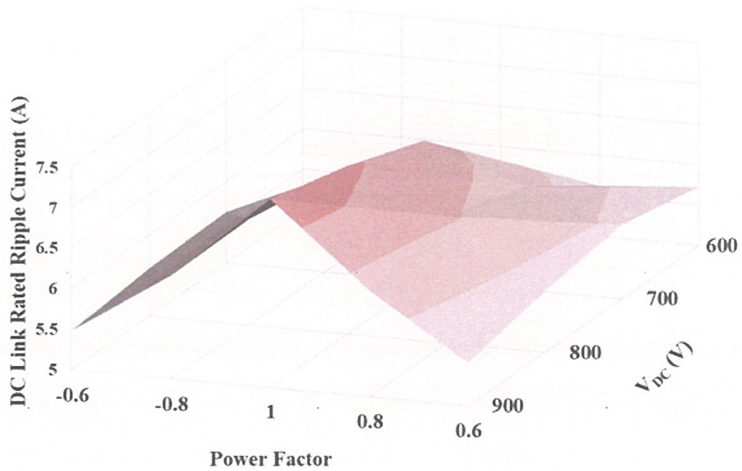

Figure 4.49: DC-link rated ripple currents with unbalance controller at grid condition 8.

Table 4.73: DC-link rated ripple currents with unbalance controller at grid condition 1

DC-Link Voltage	Power Factor				
	-0.6	-0.8	1	0.8	0.6
900	5.305054	5.81517	6.599196	5.990573	5.524385
800	5.362657	5.740219	6.211415	5.937489	5.685841
700	5.772491	5.289798	5.435503	5.597745	5.682242
600	4.755884	4.138977	3.440675	4.866112	5.557033

Table 4.74: DC-link rated ripple currents with unbalance controller at grid condition 2

DC-Link Voltage	Power Factor				
	-0.6	-0.8	1	0.8	0.6
900	5.266744	5.68211	6.371858	5.90315	5.538932
800	5.288646	5.550333	5.908475	5.799018	5.662408
700	5.558563	4.995936	4.96949	5.38585	5.620513
600	4.714404	3.892393	2.883693	4.801737	5.654717

Table 4.75: DC-link rated ripple currents with unbalance controller at grid condition 3

DC-Link Voltage	Power Factor				
	-0.6	-0.8	1	0.8	0.6
900	5.363932	5.96277	6.833358	6.093911	5.530842
800	5.44777	5.931562	6.503508	6.081836	5.72102
700	6.004415	5.590702	5.88691	5.833121	5.773016
600	4.925197	4.526862	4.12121	5.088247	5.592619

Table 4.76: DC-link rated ripple currents with unbalance controller at grid condition 4

DC-Link Voltage	Power Factor				
	-0.6	-0.8	1	0.8	0.6
900	5.329586	5.82854	6.603758	6.009653	5.553855
800	5.385071	5.748698	6.208894	5.953038	5.714004
700	5.799543	5.306059	5.43942	5.626645	5.724403
600	4.84956	4.235125	3.553969	4.977557	5.665817

Table 4.77: DC-link rated ripple currents with unbalance controller at grid condition 5

DC-Link Voltage	Power Factor				
	-0.6	-0.8	1	0.8	0.6
900	5.419487	6.113168	7.073863	6.197751	5.530217
800	5.522046	6.117088	6.791561	6.218283	5.741655
700	5.506636	5.875493	6.318269	6.055829	5.848935
600	5.104298	4.926705	4.781312	5.341926	5.645464

Table 4.78: DC-link rated ripple currents with unbalance controller at grid condition 6

DC-Link Voltage	Power Factor				
	-0.6	-0.8	1	0.8	0.6
900	5.221919	5.546096	6.142933	5.810863	5.539602
800	5.203485	5.35146	5.594901	5.651625	5.62672
700	4.942616	4.6987	4.49012	5.180358	5.567073
600	4.864095	4.075191	3.848915	6.804456	7.852304

Table 4.79: DC-link rated ripple currents with unbalance controller at grid condition 7

DC-Link Voltage	Power Factor				
	-0.6	-0.8	1	0.8	0.6
900	5.453616	6.132264	7.080798	6.220801	5.566598
800	5.555046	6.132472	6.79145	6.237425	5.776237
700	5.54092	5.889356	6.314166	6.077646	5.888856
600	5.18449	4.992438	4.837066	5.423436	5.737014

Table 4.80: DC-link rated ripple currents with unbalance controller at grid condition 8

DC-Link Voltage	Power Factor				
	-0.6	-0.8	1	0.8	0.6
900	5.475386	6.267831	7.321142	6.304524	5.526709
800	5.588184	6.298309	7.075942	6.562141	5.751326
700	5.630674	6.14748	6.732689	6.270056	5.912811
600	5.298961	5.339088	5.432501	5.62926	5.721946

4.3.2 DC-Link Capacitor Lifetime Expectations

The DC-Link capacitor lifetimes are calculated with (29) for each operating conditions. Ambient temperature, T_a, is taken as 85 °C for calculations. Calculated DC-Link capacitor lifetimes without unbalance controller for each condition is given in Table 4.81, 4.82, 4.83 and 4.84 for 900V, 800V, 700V, and 600V DC-Link voltages respectively. The unit of the lifetime in tables is in a thousand hours.

According to the following tables, the DC-Link capacitor lifetime is highly dependent on the operating condition of the grid-tied DC/AC converter. Especially, the change of the operating DC-Link voltage from 900V to 800V or from 700V to 600V improves the DC-Link capacitor lifetime. However, there is an edge for the exponent, n, when the DC-Link voltage goes from 800V to 700V. Therefore, the lifetime does not change much when the operating voltage is changed from 800V to 700V.

Grid condition has a minor effect on the DC-Link capacitor lifetime. Especially, the DC-Link capacitor lifetime is affected negatively with the decrease of the voltage drop on the grid for constant operating power factor and DC-Link voltage. However, the DC-Link capacitor lifetime can be affected up to 7000 h with the change of the grid condition.

Effect of the operating power factor changes with the phase angle between grid voltage and current. Generally, the DC-Link capacitor lifetime is affected positively by the change of the power factor for 900V and 800V DC-Link voltage. The increase of the phase angle between grid voltage and current rises the DC-Link capacitor lifetime for 900V and 800V DC-Link voltage. However, when DC-Link voltage is 700V or 600V, the DC-Link capacitor lifetime is affected negatively by the change of the operating power factor. Furthermore, the effect of lagging power factors on the DC link capacitor lifetime is higher than the same amount of leading power factors.

Table 4.81: DC-Link Capacitor Lifetimes without unbalance controller at 900V DC-Link Voltage

Power Factor	Grid Conditions							
	1	2	3	4	5	6	7	8
-0.6	26.1 kh	26.1 kh	26.1 kh	26.1 kh	26.0 kh	26.2 kh	26.0 kh	25.9 kh
-0.8	25.6 kh	25.7 kh	25.5 kh	25.6 kh	25.3 kh	25.9 kh	25.3 kh	25.1 kh
1	24.8 kh	25.0 kh	24.5 kh	24.8 kh	24.2 kh	25.3 kh	24.2 kh	23.9 kh
0.8	25.4 kh	25.5 kh	25.3 kh	25.4 kh	25.2 kh	25.6 kh	25.2 kh	25.1 kh
0.6	25.9 kh	25.9 kh	25.9 kh	25.9 kh	25.9 kh	25.9 kh	25.9 kh	25.9 kh

Table 4.82: DC-Link Capacitor Lifetimes without unbalance controller at 800V DC-Link Voltage

Power Factor	Grid Conditions							
	1	2	3	4	5	6	7	8
-0.6	47.0 kh	47.1 kh	46.8 kh	46.9 kh	46.7 kh	47.2 kh	46.6 kh	46.6 kh
-0.8	46.3 kh	46.6 kh	45.9 kh	46.3 kh	45.6 kh	47.0 kh	45.6 kh	45.2 kh
1	45.4 kh	46.0 kh	44.8 kh	45.4 kh	44.3 kh	46.5 kh	44.3 kh	43.7 kh
0.8	45.9 kh	46.2 kh	45.7 kh	45.9 kh	45.4 kh	46.4 kh	45.4 kh	44.7 kh
0.6	46.4 kh	46.4 kh	46.3 kh	46.3 kh	46.3 kh	46.5 kh	46.2 kh	46.3 kh

Table 4.83: DC-Link Capacitor Lifetimes without unbalance controller at 700V DC-Link Voltage

Power Factor	Grid Conditions							
	1	2	3	4	5	6	7	8
-0.6	44.2 kh	44.5 kh	43.8 kh	44.1 kh	44.6 kh	45.5 kh	44.6 kh	44.4 kh
-0.8	45.0 kh	45.4 kh	44.5 kh	45.0 kh	44.0 kh	45.9 kh	44.0 kh	43.5 kh
1	44.7 kh	45.5 kh	44.0 kh	44.7 kh	43.2 kh	46.2 kh	43.2 kh	42.4 kh
0.8	44.5 kh	44.8 kh	44.1 kh	44.4 kh	43.7 kh	45.1 kh	43.6 kh	43.3 kh
0.6	44.3 kh	44.4 kh	44.2 kh	44.3 kh	44.0 kh	44.5 kh	44.0 kh	43.9 kh

Table 4.84: DC-Link Capacitor Lifetimes without unbalance controller at 600V DC-Link Voltage

Power Factor	Grid Conditions							
	1	2	3	4	5	6	7	8
-0.6	72.7 kh	72.8 kh	72.3 kh	72.5 kh	71.9 kh	72.5 kh	71.7 kh	71.4 kh
-0.8	74.1 kh	74.6 kh	73.3 kh	73.9 kh	72.3 kh	74.2 kh	72.2 kh	71.3 kh
1	75.5 kh	76.4 kh	74.2 kh	75.3 kh	72.7 kh	74.7 kh	72.6 kh	71.0 kh
0.8	72.4 kh	72.6 kh	71.9 kh	72.2 kh	71.3 kh	67.0 kh	71.1 kh	70.5 kh
0.6	70.7 kh	70.4 kh	70.6 kh	70.4 kh	70.5 kh	63.6 kh	70.3 kh	70.2 kh

Calculated DC-Link capacitor lifetimes with unbalance controller for each condition is given in Table 4.85, 4.86, 4.87 and 4.88 for 900V, 800V, 700V, and 600V DC-Link voltages respectively. The unit of the lifetime in tables is in a thousand hours.

The unbalance controller has no significant effect on DC-Link capacitor lifetimes. It does not support or disturb the DC-Link capacitor lifetime. The capacitor lifetime only changes several ten hours with the implementation of the unbalance controller. Therefore, the unbalance controller could not be evaluated with the performance on DC-Link capacitor lifetimes.

Table 4.85: DC-Link Capacitor Lifetimes with unbalance controller at 900V DC-Link Voltage

Power Factor	Grid Conditions							
	1	2	3	4	5	6	7	8
-0.6	26.1 kh	26.1 kh	26.1 kh	26.1 kh	26.0 kh	26.2 kh	26.0 kh	25.9
-0.8	25.6 kh	25.7 kh	25.5 kh	25.6 kh	25.3 kh	25.9 kh	25.3 kh	25.1 kh
1	24.8 kh	25.0 kh	24.5 kh	24.8 kh	24.2 kh	25.3 kh	24.2 kh	23.9 kh
0.8	25.4 kh	25.5 kh	25.3 kh	25.4 kh	25.2 kh	25.6 kh	25.2 kh	25.1 kh
0.6	25.9 kh	25.9 kh	25.9 kh	25.9 kh	25.9 kh	25.9 kh	25.9 kh	25.9 kh

Table 4.86: DC-Link Capacitor Lifetimes with unbalance controller at 800V DC-Link Voltage

Power Factor	Grid Conditions							
	1	2	3	4	5	6	7	8
-0.6	47.0 kh	47.1 kh	46.8 kh	46.9 kh	46.7 kh	47.2 kh	46.6 kh	46.6 kh
-0.8	46.3 kh	46.6 kh	45.9 kh	46.3 kh	45.6 kh	47.0 kh	45.6 kh	45.2 kh
1	45.4 kh	46.0 kh	44.8 kh	45.4 kh	44.3 kh	46.5 kh	44.3 kh	43.7 kh
0.8	45.9 kh	46.2 kh	45.7 kh	45.9 kh	45.4 kh	46.4 kh	45.4 kh	44.7 kh
0.6	46.4 kh	46.4 kh	46.3 kh	46.3 kh	46.3 kh	46.5 kh	46.2 kh	46.3 kh

Table 4.87: DC-Link Capacitor Lifetimes with unbalance controller at 700V DC-Link Voltage

Power Factor	Grid Conditions							
	1	2	3	4	5	6	7	8
-0.6	44.2 kh	44.5 kh	43.8 kh	44.1 kh	44.6 kh	45.5 kh	44.6 kh	44.4 kh
-0.8	45.0 kh	45.4 kh	44.5 kh	45.0 kh	44.0 kh	45.9 kh	44.0 kh	43.5 kh
1	44.7 kh	45.5 kh	44.0 kh	44.7 kh	43.2 kh	46.2 kh	43.2 kh	42.4 kh
0.8	44.5 kh	44.8 kh	44.1 kh	44.4 kh	43.7 kh	45.1 kh	43.6 kh	43.3 kh
0.6	44.3 kh	44.4 kh	44.2 kh	44.3 kh	44.0 kh	44.5 kh	44.0 kh	43.9 kh

Table 4.88: DC-Link Capacitor Lifetimes with unbalance controller at 600V DC-Link Voltage

Power Factor	Grid Conditions							
	1	2	3	4	5	6	7	8
-0.6	72.7 kh	72.8 kh	72.3 kh	72.5 kh	71.9 kh	72.5 kh	71.7 kh	71.4 kh
-0.8	74.1 kh	74.6 kh	73.3 kh	73.9 kh	72.3 kh	74.2 kh	72.2 kh	71.3 kh
1	75.5 kh	76.4 kh	74.2 kh	75.3 kh	72.7 kh	74.7 kh	72.6 kh	71.0 kh
0.8	72.4 kh	72.6 kh	71.9 kh	72.2 kh	71.3 kh	67.0 kh	71.1 kh	70.5 kh
0.6	70.7 kh	70.4 kh	70.6 kh	70.4 kh	70.5 kh	63.6 kh	70.3 kh	70.2 kh

CHAPTER V

CONCLUSION

In this thesis, a 10 kVA grid-tied DC/AC converter is modelled and the dynamics of the DC/AC converter are observed under different operation conditions. A simulation model is created in simulation software PLECS. For case study, five different conditions are determined such as, DC-Link capacitor type, DC-Link voltage, power factor, grid conditions and an unbalance controller existence. The output current and DC-Link capacitor current of the DC/AC converter are observed during the change of the conditions.

Eight grid conditions are selected for this study. One of the grid condition is balance grid condition. the other seven versions are modelled as voltage asymmetry in grid voltages to define the unbalanced grid conditions. The effects of the unbalanced grid condition on output current quality and DC-Link current characteristics are compared to the balance power system. Furthermore, the grid-tied DC/AC converter is connected to a local distribution system for this study. A 600 kVA distribution transformer is selected as a distribution system.

The second variable is the DC-Link voltage. Four different DC-Link voltages are determined as 900V, 800V, 700V, 600V because a grid-tied inverter should be operated at different DC-Link voltage levels.

Two different DC-Link capacitor blocks are implemented to the simulation model as the film capacitor and electrolytic capacitor. The equal volume of DC-Link capacitor blocks is compared based on the DC/AC converter output current quality.

The last variable of this study is unbalance controller. An unbalance voltage controller is designed to eliminate the negative effects of the grid conditions.

The first chapter reviews the DC/AC converters and its requirements. The classification of DC/AC converters is introduced. The grid connection requirements of the inverter are discussed. Furthermore, the features of the present product are stated in this chapter.

The second chapter involves the theory for this study. The definition of power and symmetrical components of grids are explained. A piece of brief information about DC-Link capacitor types is stated in here. Lifetime model of the capacitor and the DC/AC converter topologies are also explained in chapter 2. Furthermore, closed-loop control strategies and the definition of unbalance controller are provided.

The third chapter describes the implementation of the system in the simulation model. The component models and grid conditions are discussed in this chapter.

The fourth chapter is dedicated to the results. The simulation model is also provided in this chapter. All results are given in detail.

The DC/AC converter output current quality is one of the objectives of this study. The current quality is protected by international standards like IEEE 517-2014. According to IEEE 517-2014, the output current THDs of the grid-tied inverter must be under 5%. The simulation-based study is completed. The results are categorized according to the DC-Link capacitor type and unbalance controller existence.

The electrolytic capacitor can handle all conditions in linear operation of the DC/AC converter. The output current THDs vary from 0.31% to 1.985% without unbalance controller. A DC/AC converter with electrolytic DC-Link capacitor block does not require an unbalance controller to remains stable operation because the output current THDs are under the limitations in all operating conditions. However, the output current quality is improved by the implementation of the unbalance controller. The implementation of the unbalance controller decreases the DC/AC converter output current THDs under 1% in all linear operating conditions.

Film capacitors meet the requirements of the harmonic standard under unity factor operation for almost all grid conditions without unbalance controller. The output current THDs vary from 1.098% to 5.021% at unity power factor. For unity power factor operation, the film capacitor can be relocated as the DC-Link capacitor instead of the electrolytic capacitor. However, the film capacitor does not meet the requirements for other power factor and DC-Link voltage conditions because, in several linear operating conditions the output current THD goes up to 13.827%. On the other hand, the implementation of the unbalance controller to the DC/AC converter that has film DC-Link capacitor block, the output current quality significantly improves. The film capacitor can comply with the grid harmonic requirements in all linear working regions. The output current THDs vary from 0.608% to 5.085%. Therefore, if the unbalance controller is implemented to the grid-tied inverter, the film capacitor can be replaced with the electrolytic capacitor for all linear operation condition.

There are also several nonlinear operating conditions. The non-linearity is checked from the modulation index. At grid condition 6 and 600V DC-Link voltage, the DC/AC converter goes out the linear working condition. Therefore, the increase of the grid phase voltages causes the failure of DC/AC converter.

The other observation is the effects of the operating conditions to the lifetime of electrolytic DC-Link capacitor block. A mathematical lifetime model is created to calculate the lifetime expectation of electrolytic DC-Link capacitor block. According to results, grid condition, operating power factor, and DC-Link voltage can affect the DC-Link capacitor lifetime. The electrolytic DC-Link capacitor block lifetime vary from 23.9 kh to 76.4 kh. Especially, the DC-Link voltage level affects the capacitor lifetime. Furthermore, the operating power factor has an effect on capacitor lifetime. According to the operating power power factor, lifetime of DC-Link capacitor changes up to 10 kh at any voltage level. The phase difference between grid voltage and current decreases the lifetime of the DC-Link capacitors. The grid condition effect on the capacitor lifetime is lower than other parameters but it should be considered. Therefore, while the life warranty of the grid-tied DC/AC converter is determined, these parameters are a design consideration.

Furthermore, the lifetime is also calculated with the unbalance controller, but there is no significant effect of unbalance controller to the electrolytic DC-Link capacitor block. The results are close to each other and there is only several ten hours difference between them. Therefore, the unbalance controller does not support or disturb the lifetime expectations of grid-tied DC/AC converter.

In conclusion, this thesis provides a thorough analysis, methodical design and implementation of 10 kVA grid-tied DC/AC converter in simulation software PLECS. The study shows that the operation condition and DC-Link capacitor type of grid-tied inverter highly affect the output current quality and lifetime. The study results are important for new design converters to estimate the general characteristics.

All the theory and analytical results developed in this thesis were supported by means of detailed computer simulations studies. The detailed results are stated in the thesis.

Bibliography

[1] European Photovoltaic Industry Association, "Global market outlook for photovoltaics 2014-2018," 2014.

[2] Kouro, S., Leon, J.I., Vinnikov, D., et al., "Grid-connected photovoltaic systems: an overview of recent research and emerging PV converter technology," IEEE Ind. Electron. Mag., 2015, pp. 47–61.

[3] Wang, X., Guerrero, J., Chen, Z., & Blaabjerg, F., "Distributed energy resources in grid interactive AC microgrids," 2nd IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG), 2010, pp. 806-812.

[4] E. Owen, "History [origin of the inverter]," Industry Applications Magazine, IEEE, vol. 2, no. 1, pp. 64-66, 1996.

[5] Y. Tang, P. C. Loh, P. Wang, F. H. Choo, and F. Gao, "Exploring inherent damping characteristic of LCL-filters for three-phase grid-connected voltage source inverters," IEEE Transactions on Power Electronics, vol. 27, no. 3, 2012, pp. 1433–1443.

[6] M. A. Eltawil and Z. Zhao, "Grid-connected photovoltaic power systems: technical and potential problems—a review," Renewable and Sustainable Energy Reviews, vol. 14, no. 1, 2010, pp. 112–129.

[7] Jun-Koo Kang and Seung-Ki Sul, "Control of unbalanced voltage PWM converter using instantaneous ripple power feedback", 28th Annual IEEE Power Electronics Specialists Conference, 1997, pp. 503-508.

[8] Y. Suh and T. A. Lipo, "Control scheme in hybrid synchronous stationary frame from PWM AC/DC converter under generalized unbalanced operating conditions," IEEE Trans. Ind. Appl., vol. 42, no. 3, May/Jun. 2006, pp. 825–835.

[9] Konstantin V. Khatsevskiy, Alexander I. Antonov, Tatjana V. Gonenko and Vladimir F. Khatsevskiy "The voltage asymmetry in electrical networks with single-phase load," 2017 IEEE Dynamics of Systems, Mechanisms, and Ma hines (Dynamics), 14-16 Nov. 2017 pp. 825–835.

[10] Y. Bae, T.K. Vu, and R.-Y. Kim, "Implemental control strategy for grid stabilization of grid-connected PV system based on German grid code in symmetrical low-to-medium voltage network," IEEE Trans. Energy Conversion, vol. 28, no. 3, Sept. 2013, pp. 619–631.

[11] A. Kumar, N. Gupta and V. Gupta, "A Comprehensive Review on Grid-TiedSolar Photovoltaic System," Journal of Green Engineering, 2017, pp. 213-254.

[12] B. Xiao, L. Hang, J. Mei, C. Riley, L. Tolbert, and B. Ozpineci, "Modular cascaded h-bridge multilevel pv inverter with distributed mppt for grid-connected applications," Industry Applications, IEEE Transactions on, vol. 51, no. 2, March 2015, pp. 1722–1731.

[13] T. Bruckner, S. Bernet, and H. Guldner, "The active NPC converter and its loss-balancing control," IEEE Transactions on Industrial Electronics, vol. 52, Jun 2005, pp. 855-868.

[14] S. Daher, J. Schmid, and F. L.M. Antunes, "Multilevel inverter topologies for stand-alone PV systems," IEEE Trans. Ind. Electron., vol. 55, no. 7, Jul. 2008, pp. 2703–2712.

[15] J. C. Boemer, K. Burges, P. Zolotarev, J. Lehner, P. Wajant, M. Fürst, R. Brohm, and T. Kumm, "Overview of German grid issues and retrofit of photovoltaic

power plants in Germany for the prevention of frequency stability problems in abnormal system conditions of the ENTSO-E region continental Europe," Proc. Solar Integration Workshop, Aarhus, Denmark, 2011.

[16] Technical Requirements for the Connection to and Parallel Operation with Low-Voltage Distribution Networks, VDE-AR-N 4105, 2011.

[17] IEEE Std 519^{TM}-2014, "IEEE recommended practice and requirements for harmonic control in electric power systems," IEEE Power and Energy Society, 2014.

[18] G. Petrone, G. Spagnuolo, R. Teodorescu, M. Veerachary, and M. Vitelli, "Reliability issues in photovoltaic power processing systems," IEEE Trans. Ind. Electron., vol. 55, no. 7, Jul. 2008, pp. 2569–2580.

[19] Y. Song and B. Wang, "Survey on reliability of power electronic systems," IEEE Trans. Power Electron., vol. 28, no. 1, Jan. 2013, pp. 591–604.

[20] H. S.-H. Chung, H. Wang, F. Blaabjerg, and M. Pecht, "Reliability of Power Electronic Converter Systems," IET, 2015.

[21] A. Sangwongwanich, Y. Yang, D. Sera, and F. Blaabjerg, "Lifetime evaluation of grid-connected PV inverters considering panel degradation rates and installation sites," IEEE Trans. Power Electron., vol. 33, no. 2, Feb. 2018, pp. 1225–1236.

[22] U. Scheuermann and U. Schilling, "Impact of device technology on cosmic ray failures in power modules," IET Power Electron, 2016, pp. 2027–2035.

[23] National Renewable Energy Laboratory, "On the path to sunshot: The role of advancements in solar photovoltaic efficiency, reliability, and costs," Tech. Rep. No. NREL/TP-6A20-65872, 2016.

[24] L. M. Moore and H. N. Post, "Five years of operating experience at a large, utility-scale photovoltaic generating plant," Progress Photovoltaics: Res. Appl., vol. 16, no. 3, 2008, pp. 249–259.

[25] IEEE Std 1459-2010, IEEE Trial-Use Standard Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions, New York, 2010.

[26] C. Fortescue, "Method of symmetrical coordinates applied to the solution of polyphase networks," Trans. AIEE, vol. 37, 1918, pp. 1027–1140.

[27] EPCOS, "Film Capacitors - reliability with a long operating life," Components, Application & Cases, Edition 2, 2007.

[28] Karanayil, B., V.G. Agelidis, and J. Pou. "Evaluation of DC-link decoupling using electrolytic or polypropylene film capacitors in three-phase grid-connected photovoltaic inverters," in Industrial Electronics Society, IECON 2013-39th Annual Conference of the IEEE. 2013. IEEE

[29] W. Yan, L.Meek , S.M.H. Nabavi and M. Abshar "A study of the DC link capacitor selection for 250kW battery energy storage system," in Australasian Universities Power Engineering Conference, AUPEC 2014.

[30] H. Wang and F. Blaabjerg, "Reliability of capacitors for DC-Link applications in power electronic converters-an overview," IEEE Trans. Ind. Appl., vol. 50, no. 5, DOI 10.1109/TIA.2014.2308357, Sep./Oct. 2014, pp. 3569- 3578.

[31] TDK, "Aluminum electrolytic capacitors - general technical information," December 2016.

[32] TDK, "Film capacitors - general technical information," June 2018.

[33] C. Siedle and V. D. Ingenieure, "Comparative Investigations of Charge Equalizers to Improve the Long-Term Performance of Multi-cell Battery Banks," vol. 245, VDI Verlag, 1998.

[34] P. Venet, A. Lahyani, G. Grellet, A. Ah-Jaco. "Influence of aging on electrolytic capacitors function in static converters: Fault prediction method," European Physical Journal: Applied Physics, EDP Sciences, pp.71-83, 1999.

[35] J. Ho, T. R. Jow, and S. Boggs, "Historical Introduction to Capacitor Technology," IEEE Electrical Insulation Magazine, vol. 26 (1), 2010, pp. 20-25.

[36] VISHAY, "Aluminum Capacitors in Power Supplies," Engineering Solutions, 2018.

[37] A. Albertsen, "Electrolytic Lifetime Estimation," JIANGHAI EUROPE GmbH, 2010.

[38] S. Roberts, "AC/DC Book of Knowledge," RECOM, 2018.

[39] Z. Ozkan and A. M. Hava, "Three-phase inverter topologies for grid connected photovoltaic systems," Proc. of the Intern. Power Electr. Conf., Japan, 2014, pp. 498-505.

[40] SEMIKRON, "3L NPC & TNPC topology", Application note: AN-11001, revision 5, February 2015.

[41] A.M. Hava, R.J. Kerkman, and T.A. Lipo, "Simple analytical and graphical methods for carrier-based PWM-VSI drives," IEEE Trans. Power Electron., vol. 14, no. 1, Jan. 1999, pp. 49–61.

[42] N. Prabaharan, and K. Palanisamy, "A comprehensive review on reduced switch multilevel inverter topologies, modulation techniques and applications," Renewable and Sustainable Energy Reviews, 76, 2017, pp. 1248-1282.

[43] Z. Özkan, A.M. Hava, "Dc-bus ripple current characterization of three-phase 2/3L-VSIs considering the spectral characteristics," ICPE 2015-ECCE Asia, Seoul, Korea, June 2015.

[44] Z. Özkan, A.M. Hava, "Output ripple performance evaluation and comparison of 2L-VSI and 3L-VSI considering the spectral characteristics," ICPE 2015-ECCE Asia, Seoul, Korea, June 2015.

[45] S. Tahir, J. Wang, G.S. Kaloi, M. Hussain, "Digital control techniques based on voltage source inverters in renewable energy applications: a review," Electronics, 2018.

[46] S. Tahir, J. Wang, G.S. Kaloi, M. Hussain, "Robust digital deadbeat control design technique for 3 phase VSI with disturbance observer," IEICE Electron. Express, 2017.

[47] Lim, J.S., Park, C., Han, J., et al., "Robust tracking control of a three-phase DC–AC inverter for UPS applications', IEEE Trans. Ind. Electron., 2014, pp. 4142–4151.

[48] J. M. Espi Huerta, J. C. Moreno, J. R. Fischer, and R. G. Gil, "A synchronous reference frame robust predictive current control for three-phase grid-connected inverters," IEEE Transactions on Industrial Electronics, March 2010, pp. 954–962.

[49] J. Miret, A. Camacho, M. Castilla, L. G. de Vicuna, and J. Matas, "Control scheme with voltage support capability for distributed generation inverters under voltage sags," IEEE Trans. Power Electron., vol. 28, no. 11, Nov. 2013 , pp. 5252–5263.

[50] Z. Liu, J. Liu, and Y. Zhao, "A unified control strategy for three-phase inverter in distributed generation," Power Electronics, IEEE Transactions on, vol. 29, no. 3, 2014 , pp. 1176–1191.

[51] Y. Li, S. Jiang, J.G. C. Rivera, F. Peng, "Modeling and control of quasi-Z-source inverter for distributed generation applications," IEEE Trans. Ind. Electron., Apr 2013, pp. 1532-1541.

[52] M. Ebadi, J. Mahmood, and M. Javad Shokrollahi, "Voltage look-up table method to control multilevel cascaded transformerless inverters with unequal DC rail voltages," IET Power Electron., vol. 7, no. 9, Jul. 2014, pp. 2300–2309.

[53] N. Mohan, T. M. Undeland, and W. F. Robbins, Power Electronics: Converters, Applications and Design. New York Wiley, 1995.

[54] V. Kaura, V. Blasko, "Operation of a phase locked loop system under distorted utility conditions," IEEE Transactions on Industrial Electronics, Jan./Feb. 1997, pp. 58-63.

[55] J. M. Guerrero, J. C. Vasquez, J. Matas, M. Castilla, and L. G. de Vicuna, "Control strategy for flexible microgrid based on parallel line-interactive UPS systems," IEEE Trans. Ind. Electron., vol. 56, no. 3, Mar. 2009, pp. 726–736.

[56] Y. A.-R. Mohamed and E. F. El-Saadany, "Adaptive discrete-time gridvoltage sensorless interfacing scheme for grid-connected dg-inverters based on neural-network identification and deadbeat current regulation," IEEE Trans. Power Electron., vol. 23, no. 1, Jan. 2008, pp. 308–321.

[57] G. Shen, D. Xu, L. Cao, and X. Zhu, "An improved control strategy for grid-connected voltage source inverters with an LCL filter," IEEE Trans. Power Electron., vol. 23, no. 4, Jul. 2008, pp. 1899–1906.

[58] I. J. Gabe, V. F. Montagner, and H. Pinheiro, "Design and implementation of a robust current controller for VSI connected to the grid through an lcl filter," IEEE Trans. Power Electron., vol. 24, no. 6, Jun. 2009, pp. 1444–1452.

[59] T. Horik, Q.-C. Zhong, "A current-control strategy for voltage-source inverters in microgrids based on H^∞ and repetitive control," IEEE Trans. Power Electron., vol. 26, no. 3, March 20011, pp. 943-952.

[60] A. Timbus, M. Liserre, R. Teodorescu, P. Rodriguez, and F. Blaabjerg, "Evaluation of current controllers for distributed power generation systems," IEEE Trans. Power Electron., vol. 24, no. 3, Mar. 2009, pp. 654–664.

[61] M. Merai, M. W. Naouar, I. Slama-Belkhodja, E. Monmasson, "An adaptive PI controller design for dc-link voltage control of single-phase grid-connected converters," IEEE Trans. Ind. Electron., vol. 66, no. 3, August 20019, pp. 6241-6249.

[62] H. Akagi, A. Nabae, and S.Atoh "Control strategy of active power filters using multiple voltage-source PWM converters", IEEE Trans. on Ind. Appl. v01.22, no.3, 1986, pp. 460-465.

[63] K. Ahmed, S. Finney, and B. Williams, "Passive filter design for three-phase inverter interfacing in distributed generation," in Proc. Compatibility Power Electronics (CPE'07), Jun. 2007, pp. 1–9.

[64] Y. Kim, H. Cha, B.M Song, and K.Y Lee, "Design and control of a grid-connected three-phase 3-level NPC inverter for building integrated photovoltaic systems," in Proc. of IEEE PESISGT'12. Washington, DC, pp. 1-7, January 2012.

[65] Schneider-electric, "HV/LV Distribution Catalog," November 2004 Available: http://mt.schneider-electric.be/main/tfo/catalogue/an_iec.pdf. [Accessed March 07, 2019].

[66] Yan Li, Longnv Li, Yongten Jing, Fangxu Han, Shuangpeng Li, Fengge Zhang, "Calculation and analysis of leakage magnetic field and short circuit impedance in split winding transformer," in International Conference on Electrical Machines and Systems, 2013, pp. 2263-2266.

[67] TDK, B43544 serie aluminum electrolytic capacitors catalog, December 2016.

[68] TDK, B32774 - B32778 serises Metallized Polypropylene Film Capacitors catalog, June 2018.

[69] A.M. Hava, R.J. Kerkman, and T.A. Lipo, "Carrier-based PWM-VSI overmodulation strategies: analysis, comparison, and design," IEEE Trans. Power Electron., vol. 13, no. 4, July 1998, pp. 674-689.

VITA

Mert Serdar Bilgin was born in 1992 in Denizli. He received B.Sc degree of Electrical and Electronics Engineering from Dokuz Eylul University in 2016. He is a Power Electronic Hardware Design and Control Engineer. He has the experience to design voltage source inverters, DC/DC converter topologies, experience to analyze engineering problems, evaluate designs and recommend alternatives. He has a good understanding of hardware product development design and closed-loop control algorithm development. He has been working at Vestel Electronic R&D department.