A STUDY ON SINGLE PHASE-SHIFT HIGH-POWER DUAL ACTIVE BRIDGE (DAB) CONVERTER FOR PV APPLICATION

A thesis submitted in partial fulfilment of the requirements for the award of the degree of

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Submitted by

SHUVANGKAR DARNAL

Examination Roll No: M4CTL24008

Registration No: 163527 of 2022 – 2023

Under the Guidance of

Dr. Debashis Chatterjee

Professor,

Department of Electrical Engineering
Jadavpur University, Kolkata – 700032

DEPARTMENT OF ELECTRICAL ENGINEERING

FACULTY OF ENGINEERING AND TECHNOLOGY

JADAVPUR UNIVERSITY

KOLKATA – 700032, WEST BENGAL, INDIA

2024

DEDICATED

TO MY BELOVED FAMILY MEMBERS

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……………………………

Supervisor,

Dr. Debashis Chatterjee, Professor,

Department of Electrical Engineering

Jadavpur University,

Kolkata –700032

…………………………..

Head of the Department,

Dr. Biswanath Roy,

Department of Electrical Engineering

Jadavpur University,

Kolkata -700032

………………………………………………………

DEAN,

Faculty of Engineering and Technology,

Jadavpur University, Kolkata – 700032

CERTIFICATE OF APPROVAL

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Name: Shuvangkar Darnal

Examination Roll No.: M4CTL24008

Class Roll No: 002210804013

Registration No: 163527 of 2022 – 2023

Thesis Title: **A Study on Single Phase-Shift High- Power Dual Active Bridge (DAB) Converter for PV Application**

Place: Kolkata

Date: Signature

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Date ………………………………………….

Shuvangkar Darnal,

Master in Control System Engineering, Department of Electrical Engineering, Jadavpur University, Kolkata – 700032

ABSTRACT

The Single Phase-Shift (SPS) High-Power Dual Active Bridge (DAB) converters has been studied. This study investigates the Single Phase-Shift control of the High-Power DAB converter, particularly in PV application. It includes the development of a mathematical model, simulations using MATLAB, and experimental validations. It includes calculations of Output Power with varying Phase Angles and switching frequencies. A PV Array "SunPower SPR-295E-WHT-D" has been used with Irradiance as 1000W/m^2 and Temp. 25^0. A thorough analysis has been done to examine the performance of a DAB when used in PV application scenario and results and data have been found out to learn how power changes with Phase Angle and the optimum operating point has been derived. The operating Switching Frequencies that have been used are 30kHz, 50Khz and 75kHz respectively and the Phase angle is varied from 15^0 to 180^0. Losses have not been considered throughout the analysis carried on in this work.

Keywords: *Dual Active Bridge (DAB), Switching frequency, PV array, phase angle.*

LIST OF ABBREVIATIONS

Abbreviation	Full-Form
SAB	Single Active Bridge
DAB	Dual Active Bridge
DC	Direct Current
AC	Alternating Current
ZVS	Zero-Voltage Switching
ZCS	Zero-Current Switching
PV	Photo Voltaic
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
IGBT	Insulated Gate Bipolar Transistor
EMI	Electromagnetic Interference
PSM	Phase-Shift Modulation
PWM	Pulse-Width Modulation
PFC	Power Factor Correction
SPSM	Single Phase-Shift Modulation
DPSM	Dual Phase-Shift Modulation
TPSM	Triple Phase-Shift Modulation
DPSC	Dual Phase-Shift Control
MBC	Model-Based Control
THD	Total Harmonic Distortion

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CHAPTER – I

Introduction

1.1. History of High-Power Dual Active Bridge Converter

Dual Active Bridge (DAB) converter was introduced in the late 1980s and early 1990 as a prospective topology for high power DC-to-DC conversion. Early research was concentrated on the basic operation of DSRs as well as their ability to provide bidirectional energy transfer, which is ideal for applications that need a battery capable of both charging and discharging. The earliest works, including the seminal study of Kheraluwala et al. [1] The DAB itself was shown to convert voltage with high efficiency and zero-voltage switching by already back in 1992.

The DAB Converter Has Made A Huge Change Over The Years Researchers have been studying different control strategies, modulation techniques and transformer designs in order to improve its performance. Semiconductor technology advances have also benefited the DAB's evolution, allowing greater operating frequencies and more efficient thermal management. These developments have solidified the DAB converter as a key element in state-of-the-art power electronics.

1.2. Importance of Renewable Energy and the Impact of Pollution on Climate Change

A number of advantages for electric vehicles come with dcc in fact the DAB converter including:-

Energy Efficient: A superior efficiency of the DAB converter results in minimal energy lose during charging and discharging cycles which allows a higher range and throughput for EVs.

Bidirectional Power Flow - be able to accommodate bi-directioanla energy transfer which is important for regenerative braking where in Energy during braking returned and store back into battery.

Compact Design: The DAB converter operates at a high frequency, which enables it to be small and light; an essential requirement for automotive use where space and weight is of paramount importance.

Better Reliability: The sophisticated control and modulation methods built into the upgraded converter lead to less stress on it, which means it lasts long under varying conditions while not compromising consistency.

Renewable Energy Integration: The DAB converter can work hand-in-hand with power generated from renewable sources, thus it would enable the EVs to be charged by using solar or wind, hence discouraging the use of non-renewable energy.

In short, Dual Active Bridge converter has gone through major transformation from its introduction to changes in control strategy, modulation technique and semiconductor level advancements with the course of time. Renewable energy is vital for mitigating climate change and protecting the environment. Transitioning to clean energy sources reduces pollution, enhances energy security, and provides economic and health benefits. Addressing pollution from fossil fuels is crucial to slowing the pace of global warming and mitigating its impacts on the planet and human societies.

1.2.1. Importance of Renewable Energy

Solar, wind, hydro and geothermal are as necessary for the sustainable future. The numerous benefits that these could provide are- Finding an alternative by reducing exploitation, Sustainable living- not interfering with the environment capital stock, Energy Security, Economic Benefits and Increased public health. No or very less greenhouse gas emission - it is well known that fossil fuels are the main reason of increase in pollution. This outperforms traditional combustion, slashing air pollution and greenhouse gas emissions. A sustainable alternative to traditional sources like coal and

gas, renewable energy comes from resources that are continually restored. This means it is a renewable, non-exhaustible source of power and not like the finite fossil fuels. Using a broad mix of renewable resources also helps to decrease reliance on imported fuels and makes for greater domestic energy security.

The Renewable Sector create jobs, providing stimulus for energy infrastructure development and maintenance. Renewable energy helps in Better Air Quality and Public Health- With fewer carbon emissions renewable generation decreases pollutants, which means cleaner air that leads to better health for the community; it reduces respiratory diseases.

1.2.2. Effect of Pollution on Climate Change

Climate change: Pollution is a major contributor to climate change, specifically the burning of fossil fuels. The burning of coal, oil and natural gas emits significant quantities of carbon dioxide (CO2) as well methane (CH4), another powerful greenhouse gases. The heat trapping gases produced by this, leads to global climate change. If the levels of greenhouse gas concentrations rise due to human activities, then it will lead to Global Warming & thus increasing Earth's Average Temp leading to more number of Heatwaves.

Climate change is linked to an increase in extreme weather events (hurricanes, floods and droughts), which are becoming more frequent as well as intense; Melting of polar ice caps and glacier is the one component due to increase warming temperature contributing to rising sea levels. This is a danger to the coastal communities and ecosystems.

Increased levels of atmospheric carbon dioxide are taken up by the oceans, resulting in ocean acidification. It is harmful to marine life but in general for organisms with calcium carbonate shells or skeletons, like corals and shellfish. Climate change alters natural habitats and ecosystems, causing biodiversity loss which makes it difficult for the species to survive at the same time they struggle with their ability to adapt.

1.3. Introduction to High-Power Dual Active Bridge Converter

Dual Active Bridge (DAB) converter has been demonstrated to be an attractive topology for DC-to-DC conversion, which typically comprises two full bridges interfaced by a high-frequency transformer with minimal loss and wide range of input voltage. It has the advantage of bidirectional power flows and this property makes DAB converter suitable for both sides energy transfer applications. The features of the DAB converter are: high power conversion efficiency with voltage gain, variable frequency and operating modes along wide range to accommodate a large number of load-side conditions.

1.4. Core Components and Operation

Active Full-Bridge Circuits: Two active full-bridge circuits, one on the converter and another on the primary side of a transformer. These circuits can control the power flow independently, which results in a tighter regulation of output voltage and current.

High-frequency transformer: This particular transformer provides an electrical barrier from input to output as needed, also the step up or down of voltage. It is a high-

frequency design that results in the smaller sizes of passive components.

Bidirectional Energy Transfer: Bridges in the DAB converter are active and can be switched on both sides, which mean that energy can move in either direction. This is especially beneficial for use cases such as battery charging and the regenerative capabilities of a vehicle during braking, in which energy must be cycled on-off-on.

1.5. Developments Over the Years

Over the years, DAB converter has seen several developments. To enhance the dynamic performance and efficiency of this conversion, the converter utilises advanced control strategies. Thus, a variety of custom method can be analyzed as evident by the phase shift control approach in this case, leading to more performance enhancement for other operation modes. Novel techniques to achieve ZVS and lossless switch turn-on/off, which can add flexible mode transitions by clever modulation schemes. These techniques in turn, improve the overall efficiency and reliability of converter.

Higher power levels require proper thermal managements as well. It is now the topic of research focusing to heat dissipation and how it can be cooled down or with efficiency enough for stable operation while high power densities. The evolution of silicon carbide (SiC) and gallium nitride (GaN) have enabled better thermal performances & higher switching frequencies. By reducing conduction and switching losses, these materials are believed to increase the efficiency of DAB converters.

1.6. Applications and Benefits for Renewable Energy System

The DAB converter is widely used for its high efficiency and bidirectional power flow support such as

Renewable Energy Systems- Used in solar and wind power systems to control energy stores, storage throughout batteries or the grid.

DAB converter for Electric Vehicles (EVs): The DAB Converter forms a part of EV charging systems to facilitate transfer of energy between battery and power grid or charger.

It provides a way to balance charge of battery and discharge, It governed the management of energy in structure according to charging and discharging cycle.

Grid-Tied Energy Storage: Both solar and DAB converter support grid stability through the management of energy flow between storage systems with power grid.

Its applications in renewable energy systems and electric vehicles highlight its importance in modern power electronics, offering efficient, reliable, and versatile solutions for energy management.

1.7. Working Principle of a High-Power Dual Active Bridge Converter

The DAB converter is a high-power DC-to-DC converter topology for high power application, two-directional of power transfer and also the efficiency must be at highest level. A detailed explanation of its interworking follows since there are relatively extensive interactions between some core components within: two active full-bridge circuits and a high-frequency transformer coupled with the controls, which manage power flow.

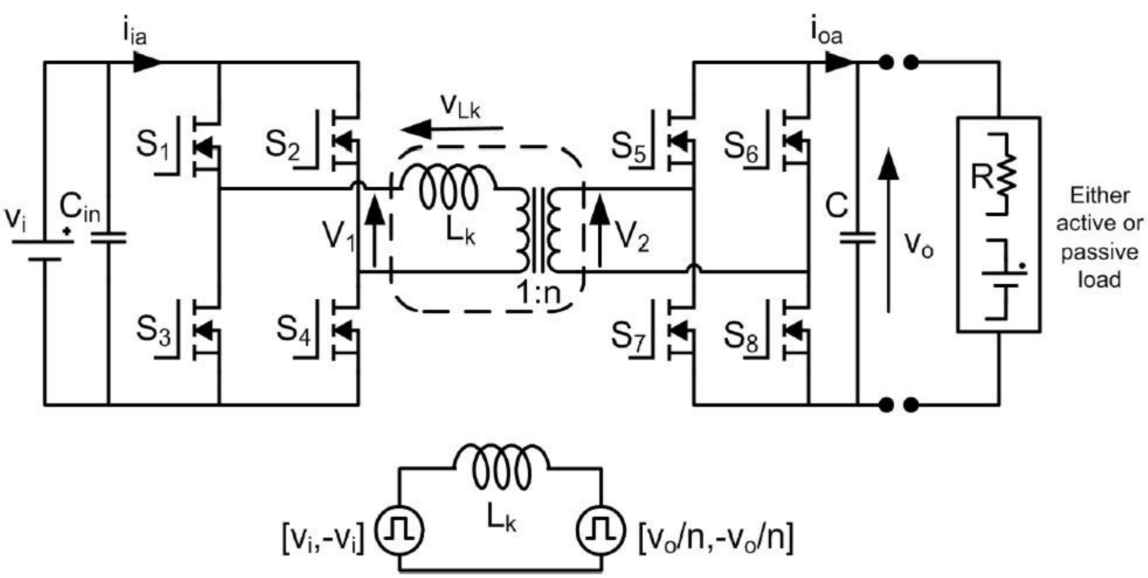


Fig.1: Circuit Schematic of a Dual Active Bridge Converter [31]

The circuit schematic of the single-phase DAB dc-to-dc converter is shown in Fig.1. The DAB dc-to-dc converter operates on a fairly simple principle. Two active bridges are phase shifted from each other and interfaced via a transformer to control the quantity of power flow from one dc voltage source to the other. This enables a fixed frequency, square-wave mode of operation and the use of the transformer's leakage inductance as the primary energy transfer element. Under idealized conditions, the output power is calculated as

$$P_O = \frac{{V_i}^2}{X_L} d\emptyset \left(1 - \frac{|\emptyset|}{\pi}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where,

$$X_L = \omega L\,, \quad d = \frac{V_o}{NV_i}$$

and V, is the input dc voltage, V, is the output dc voltage, w is the switching frequency in radians per second, L is the primary-referred leakage inductance, N is the transformer turns ratio, and + is the phase shift between the input and output bridges. The family of output power versus phase-shift curves shown in Fig. 2 using d as the parameter for both forward and reverse power flow. Positive phase-shifts occur when the source side bridge leads the load side bridge during forward power flow; negative phase-shifts occur when the load side bridge leads the source side bridge. The soft switching zone for all devices has been identified. Full control range under soft switching is achievable for d = 1 and, hence, is usually chosen as a convenient design point. For buck (d < 1) or boost (d > 1) operation, the control range is reduced under soft-switching conditions in both the quadrants. The output voltage vs output current characteristic of the converter is a more helpful piece of information for the power supply designer. Figure 3 depicts this information as a nomogram. The bold curves enclose the DAB converter's functioning zone under soft-switching conditions. At d = 1, full control under soft switching is possible. The soft-switching zone shrinks as R + x increases under lightly loaded situations. The operational phase shift, +, is given by the intersection of the constant d lines and the constant R lines (load lines). Similarly, the intersection of the constant + and constant R lines represents the converter's operating d. A nomogram of this type is quite useful for quickly determining whether or not an operational point is in the soft-switching area. The preceding analysis was performed under the assumption that the transformer magnetizing inductance is unlimited and that the device snubber capacitances are negligible. The sections that follow investigate the effect of these settings on the soft-switching region of operation for the dual active bridge dc-to-dc converter.

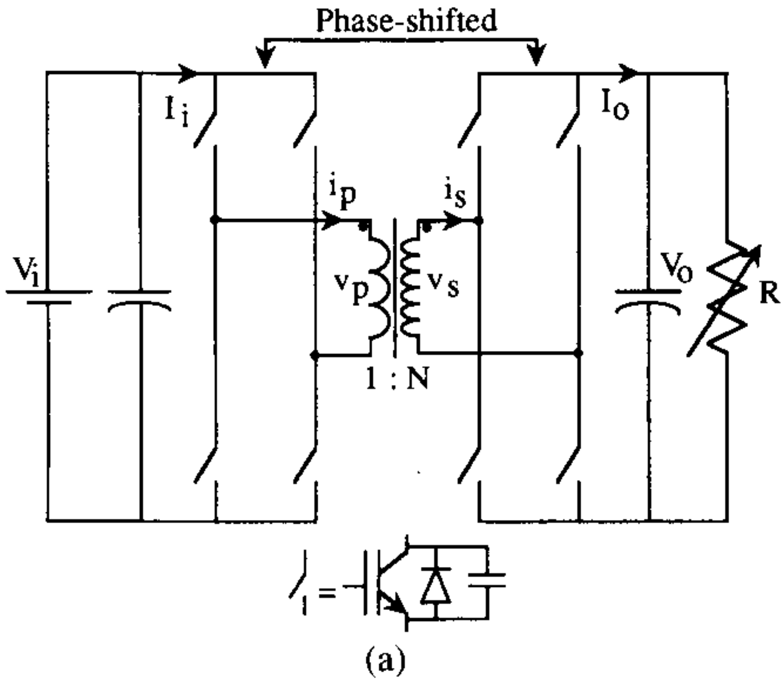


Fig. 2. Circuit schematic of single phase Dual Active Bridge DC-DC Converter [1]

WORKING PRINCIPLE:

The Dual Active Bridge (DAB) converter (shown in Figure 2) is a bidirectional DC/DC converter based on two active bridges interfaced by a high-frequency transformer (with a large effect from its leakage inductance), allowing power flow in both directions in the case of active load. Each bridge is programmed to generate a high-frequency square-wave voltage at its transformer terminals (v_i , v_o) with a constant duty cycle (50%). Given the presence of the transformer's leakage inductance, which has a controllable and known value, the two square waves can be correctly phase shifted to control the power

flow from one dc-source to the other, allowing for bidirectional power transmission. The bridge, which generates the leading square wave, supplies power.

STEADY STATE ANALYSIS:

The main waveforms of the DAB converter shown in Figure 2 can be seen in Figure 3. All the elements in this study are assumed to have no losses and all the waveforms shown are ideal. The primary bridge is composed by S1, S2, S3 and S4. The gate signals of S1 and S4 are the same. The gate signals of S2 and S3 are also identical. The gate signals of S1 and S2 are complementary 50% duty cycle signals. With this control signals, the voltage V_1, with values $\pm v_i$, is generated in the primary side of the transformer.

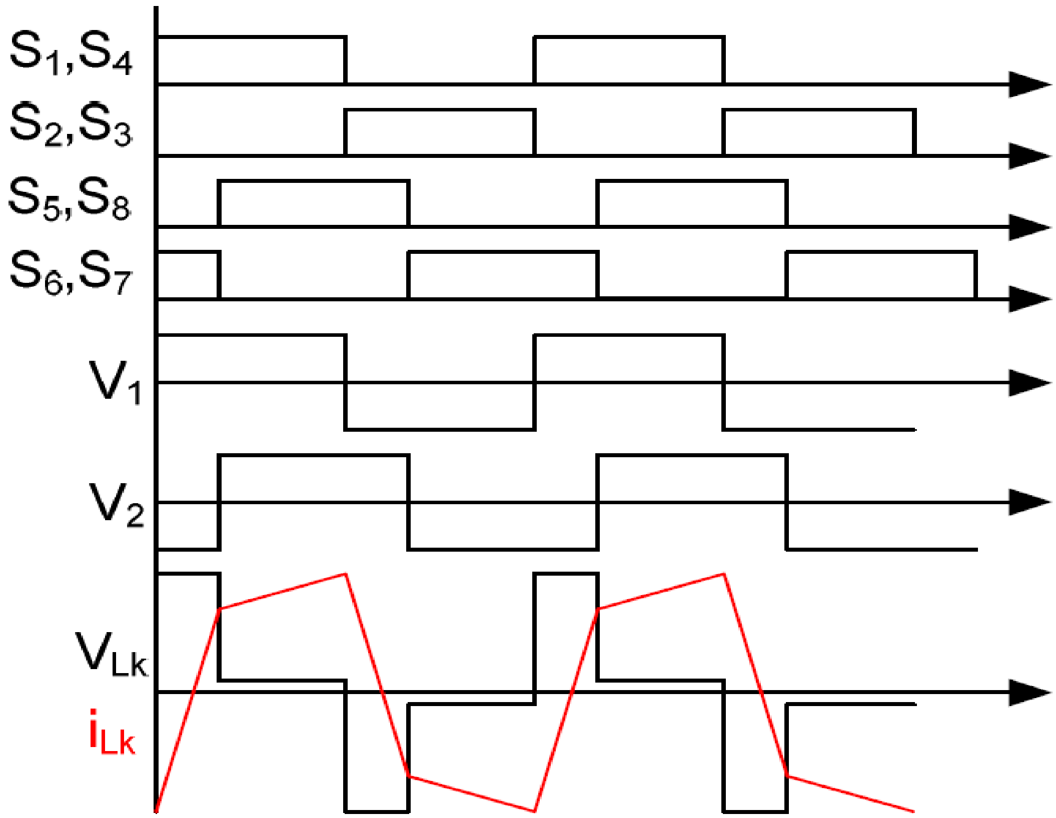
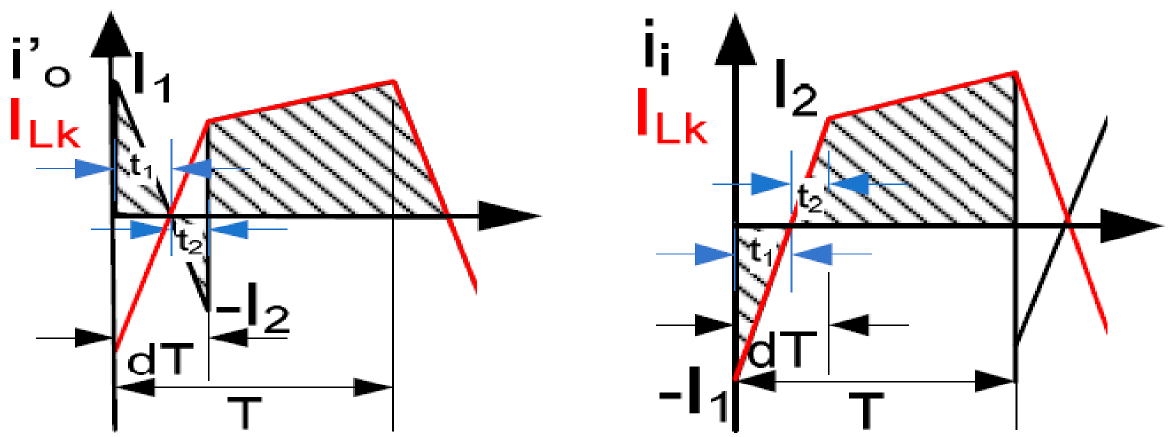


Fig 3. Waveforms [31]

In a similar way, a voltage V_2 (with values $\pm v_o$) is generated in the secondary side of the transformer, by controlling the switches of the secondary bridge (S5, S6, S7 and S8). All the control signals of the secondary bridge are similar to the signals of the primary, but with a certain phase shift. These two phase shifted signals (V_1 and V_2) generate a voltage (V_{Lk}) in the leakage inductance (L_k) of the transformer and a certain current flows through it. This current is controlled by the phase shift between the primary and secondary voltages of the transformer. Once the current through L_k is determined, the input and the output current can be evaluated, as Figure 4 shows. In this figure all the currents are referred to the primary side of the transformer. Due to the symmetry of the circuit, it is only necessary to deduce the equations for a half cycle. Using Faraday's law, and considering the representation of the quantities of the output current in Figure 4(a), equations (1) and (2) are obtained, for the two different states of the converter in a semi-period.



(a) (b)

Fig.4. Waveform of **(a)** Output current and **(b)** Input current [31]

For 0 < t < Dt → $v_i + v_o' = L_k \frac{I_1+I_2}{dT}$ …………..(1)

and for dT < t < T → $v_i - v_o' = L_k \frac{I_1-I_2}{dT}$ …………….(2)

being $V_o' = \frac{V_o}{n}, \frac{I_1}{t_1} = \frac{I_2}{t_2}$ and $t_1 + t_2 = dT$

solving this set of equations we obtain

$I_1 = \frac{T}{2L_k}(2v_o'd + v_i + v_o')$ ………………….(3)

$I_2 = \frac{T}{2L_k}(2v_i d - v_i + v_o')$ …………………(4)

$t_1 = T\left(\frac{2v_o' d + v_i - v_o'}{2(v_o' + v_i)}\right)$ ………………….(5)

$t_1 = T\left(\frac{2v_i d + v_o' - v_i}{2(v_o' + v_i)}\right)$ ………………….(6)

The average current injected into the output cell (C and load), i_{oa} (Figure 2) is:

$i_{aa} = \frac{1}{T}\left\{\frac{1}{2}I_1 t_1 - \frac{1}{2}I_2 t_2 + (1-d)TI_2 + (1-d)T\frac{1}{2}(I_1 - I_2)\right\}$ …………………(7)

From (3), (4), (5), (6), we can rewrite equation (7) as,

$i_{aa} = \frac{(1-d)dTv_i}{L_k}$ …………………..(8)

The relation between the input and output voltage can be obtained as,

$M = \frac{v_o}{nv_i} = \frac{d(1-d)TR}{Ln^2} = d(1-d)k$ …………………..(9)

Maximum output voltage is achieved at a duty cycle of 50% as (8) and (9) demonstrate. Using the same analysis than the one used to obtain the average output current, the average input current can be obtained, which expression is shown in equation (10).

$i_{aa} = \frac{1}{T}\left\{\frac{1}{2}I_2 t_2 - \frac{1}{2}I_1 t_1 + (1-d)T\frac{1}{2}(I_1 - I_2)\right\}$

$i_{aa} = \frac{Td(1-d)v_o}{nL}$ (10) [31]

1.7.1. Operation Modes

The DAB converter operates in different modes depending on the direction of power flow and the voltage levels on the primary and secondary sides. The primary modes include:

Forward Mode: Power is transferred from the primary to the secondary side.

Reverse Mode: Power is transferred from the secondary to the primary side, enabling bidirectional energy transfer.

Idle Mode: The converter is in a non-operational state where no power transfer occurs.

1.7.2. Phase-Shift Control

The key control strategy for the DAB converter is phase-shift modulation, which adjusts the phase difference between the switching signals of the primary and secondary bridges. This control mechanism enables precise regulation of power flow and is described as follows:

Each bridge generates a square wave voltage by switching its respective transistors on and off in a specific sequence.

The primary bridge generates a square wave that alternates between positive and negative input voltage, V_{in}.The secondary bridge generates a square wave at the output voltage, V_{out} , which is also alternating.

The power transferred depends on the phase shift, φ between primary and secondary square waves. The voltage difference appears on opposite ends of the core, inducing a flow of current from one terminal to another which transfers power from primary side to secondary ones. The phase shift controls the direction and magnitude of power flow; positive (negative) values corresponding to forward (reverse) power transfer.

1.7.3. Power Transfer Mechanism

ZVS is employed to reduce switching losses by ensuring that the switches turn on and off when the voltage across them is zero. The phase shift control facilitates ZVS by creating the necessary conditions during the switching transitions.

During operation, the current flows through the transformer’s windings and the switches of the active bridges, transferring energy from the input to the output. The high-frequency transformer enables efficient energy transfer with minimal losses, aided by the precise control of the phase shift.

The DAB converter’s ability to handle bidirectional power flow is crucial for applications like battery charging and discharging in electric vehicles and energy storage systems.

In forward mode, energy flows from the input source (e.g., a DC power supply or battery) to the output load (e.g., another battery or DC bus). The primary bridge generates a phase-shifted square wave relative to the secondary bridge, driving current through the transformer and transferring energy.

In reverse mode, energy flows from the load back to the input source, such as during regenerative braking in electric vehicles. The phase shift is adjusted to reverse the direction of current flow, enabling the converter to efficiently manage bidirectional energy transfer.

The High Power Dual Active Bridge Converter operates through sophisticated control of phase-shift modulation, enabling efficient and bidirectional DC-to-DC power conversion. Its ability to minimize switching losses through ZVS and handle varying voltage levels makes it an ideal choice for high-power applications, including renewable energy systems and electric vehicles. The DAB converter's versatile operation and high efficiency are central to its widespread adoption in modern power electronics.

1.8. Control Strategies for High Power Dual Active Bridge Converter

High Power Dual Active Bridge (DAB) converters are renowned for their bidirectional power transfer capabilities and high efficiency, making them ideal for a wide range of applications such as renewable energy systems, electric vehicles, and battery storage systems. The performance of these converters heavily relies on effective control strategies. Here, we discuss several key control strategies for DAB converters, including **Single Phase Shift Modulation (SPSM), Dual Phase Shift Modulation (DPSM), Triple Phase Shift Modulation (TPSM), and hybrid modulation techniques.**

1.8.1. Single Phase Shift Modulation (SPSM)

Single Phase Shift Modulation (SPSM) is the most basic and widely used control strategy for DAB converters. It involves adjusting the phase difference between the switching signals of the primary and secondary bridges to regulate power transfer.

The phase shift (ϕ) between the primary and secondary bridge voltages determines the direction and amount of power transferred.

A positive phase shift induces forward power transfer (from the primary to the secondary side), while a negative phase shift enables reverse power transfer.

SPSM supports Zero Voltage Switching (ZVS), which minimizes switching losses by ensuring that switches turn on and off at zero voltage.

Advantages:

Simplicity in implementation and control.

Effective for a wide range of operating conditions.

Reduces switching losses through ZVS.

Limitations:

Limited ZVS range under varying load conditions.

Higher current stress on components during large power transfers.

1.8.2. Dual Phase Shift Modulation (DPSM)

Dual Phase Shift Modulation (DPSM) extends the basic SPSM by introducing an additional phase shift between the transformer primary and secondary voltages, offering more control flexibility and improved performance under varying conditions.

Two phase shifts are adjusted: one between the primary and secondary bridge voltages and another within the primary or secondary bridge.

This allows more precise control over power transfer and better management of switching conditions.

Advantages:

Enhanced control over power transfer.

Improved efficiency under wide load variations.

Better ZVS range compared to SPSM.

Limitations:

Increased complexity in control implementation.

Requires more sophisticated control algorithms and hardware.

1.8.3. Triple Phase Shift Modulation (TPSM)

Triple Phase Shift Modulation (TPSM) further extends the control flexibility by introducing three independent phase shifts, allowing for optimal control over power transfer and efficiency.

Three phase shifts are controlled: one between the primary and secondary bridge voltages, and one within each of the primary and secondary bridges.

This provides maximum flexibility in managing power flow, ZVS conditions, and reducing conduction losses.

Advantages:

Maximum control over operating conditions.

Optimal efficiency and reduced losses.

Enhanced performance under dynamic load conditions.

Limitations:

High complexity in control implementation.

Requires advanced digital control systems.

1.8.4. Hybrid Modulation Techniques

Hybrid modulation techniques combine features of SPSM, DPSM, and TPSM to optimize performance across various operating conditions. These strategies aim to balance the trade-offs between simplicity, control flexibility, and efficiency.

Hybrid modulation dynamically switches between different phase shift strategies based on real-time operating conditions.

This approach leverages the strengths of each modulation technique to maintain optimal performance.

Advantages:

Adaptability to a wide range of operating conditions.

Optimized efficiency and performance.

Enhanced reliability and robustness.

Limitations:

Increased control complexity.

Requires sophisticated control algorithms and hardware.

1.8.5. Predictive and Adaptive Control Strategies

Predictive and adaptive control strategies use advanced algorithms to anticipate and respond to changes in operating conditions, further enhancing the performance of DAB converters.

Predictive control uses mathematical models to forecast future states and adjust control parameters proactively.

Adaptive control continuously monitors operating conditions and dynamically adjusts control parameters to maintain optimal performance.

Advantages:

Improved dynamic response and stability.

Enhanced efficiency and reduced losses under varying conditions.

Greater adaptability to unforeseen changes in load and input.

Limitations:

High computational requirements.

Complexity in implementation and tuning.

1.9. Resonant and Soft-Switching Techniques

Resonant and soft-switching techniques aim to minimize switching losses and electromagnetic interference (EMI) by ensuring that switching transitions occur under favorable conditions.

Resonant control uses resonant circuits to achieve ZVS and Zero Current Switching (ZCS), reducing switching losses. Soft-switching techniques modify the switching process to minimize energy dissipation during transitions.

It has advantages like significant reduction in switching losses and EMI, improved overall efficiency, enhanced reliability and longevity of components.

However, complexity in circuit design and control implementation is a challenge
It also requires precise tuning and control algorithms.

CHAPTER – II

Literature Review

2.1. Literature Survey

Kheraluwala et al. [1]

The paper "Performance Characterization of a High Power Dual Active Bridge DC-to-DC Converter" by Kheraluwala et al. (1992), this is the most complete work on DAB conversions mainly oriented for high-power applications. I wish to extract the following main points from these literature: The DAB converter is its ability for bi-directional power flow characteristic that makes it suitable for several applications like electric vehicles, renewable energy systems and more electrical aircraft. It is a dual full-bridge topology that performs power transfer and isolation between input/output by high-frequency transformer. One of the most importatnt benefits it that the DAB converter can realize zero-voltage switching (ZVS) so as to reduce switch losses and obtain higher efficiency. This paper presents the method to enable continuous soft switching operation over wide operating range through proper transformer leakage inductance and snubber capacitors design. The paper characterizes the performance of the DAB converter for efficiency, power density and thermal management. These results show that the converter can be very efficient (usually > 90%) by minimizing switching losses and optimizing passive component design. The high power density of the converter is also very key in applications with stringent space and weight limits. Various control strategies for the DAB converter are discussed, including phase-shift modulation. In this control method, the power flow is regulated with high precision which contributes into maintaining ZVS under an influential threshold during all application stages. Also discusses the effect of different control parameters on the converter performance as a whole.

Supportive experimental results from a high-power prototype corroborate the theoretical findings. The performance of the converter is confirmed using an experimental setup which demonstrates its robustness and efficiency in practical applications. Kheraluwala et al. After this report, there was an impact on high-power DC-to-DC conversion research and development that followed - in particular for regions with the requirement of high efficiency as well as a compact design.

F. Krismer et al. [2]

Krismer, Round and Kolar wrote a paper named "Performance Optimization of a High Current Dual Active Bridge with Wide Operating Voltage Range". The work focuses on improving efficiency and performance for high current DAB DC-DC converters having the capability to operate at wide voltage ranges. Major features: broad Operation Range - the DAB converter is designed for fuel cell vehicle applications in specific, which require an input voltage range from 11V to16 V on the battery side and from220Vto447 Von thefuelcellside. The need for efficiency improvement is also targeted by the authors on an advanced control strategy and reducing conduction as well as switching losses. This extends to zero-voltage switching (ZVS) which is integral in reducing the power losses and aiding in overall performance. It shows that using phase-shift control and other methods to effectively manage the power flow among different stages keeps performance at an optimum over a wide voltage range. These approaches can achieve very high efficiency and reliability in practical applications. In practice conservative optimizations in real-world scenarios are supported by experimental results, which validate the theoretical assumptions.

This work stands as an important contribution for the enhancement of DAB converter performance in scenarios with wide-range operating voltage and high efficiency requirements.

B. Zhao et al. [3]

The paper "Overview of Dual-Active-Bridge Isolated Bidirectional DC–DC Converter for High-Frequency-Link Power-Conversion System" by Biao Zhao, Qiang Song, Wenhua Liu and Yandong Sun presents a comprehensive review on the Dual Active Bridge(DAB) converters with focus also targeted to its application in high frequency link power conversion system. The DAB converter is a bidirectional and green power conversion solution, so it can be beneficial to various users in direct drives from renewable energy systems such as photovoltaic panels or wind turbines electrolysis plants for hydrogen production electric autonomous vehicles or electrified public transportation grids with gas distribution average-level local community board stations that does not lend itself well to AC networks future hybrid aerospace mission management where order-order components (like APLaTMs) have significant APULs multiple cycle battery packs ranging between 35-48 VDC payloads payload lifts downstream of spaceX superheavy lift launches which are likely capsules. This paper explains the key benefits of DAB converters that they can be used to achieve high power density, galvanic isolation and enable bi-directional power flow. These are important features to meet the needs of today's flexible and efficient power systems though

energy management. The paper further addresses the operational principles of DAB converters, and underscores phase-shift control when obtaining zero-voltage switching. Switching losses in the converter are reduced and improve overall efficiency of the converter with this control strategy. The authors also describe several modulation techniques and control strategies consequently developed aiming at improving the performance of DAB converters over different points in its operation zone. In addition, it discusses the problems in DAB converters for obtaining large voltage gain and working at high frequency. Among them, the article discusses many types of design concepts and imagination - to jump these obstacles including materials of high-performance-adhesive-type solution or as far out there as complicated control algorithms.

In summary, this systematic review highlights the importance of DAB converters in high-frequency power conversion fields and gives precious suggestions for their design and optimization to understand better overall. This paper also; concludes with the research and development requirement that is necessary to improve both performance (for some applications) or applicability of DAB converters in future power systems.

R. W. DeDoncker et al. [4]

This paper presents a three-phase soft-switched DC-DC converter designed for high power density applications. At high power the converter is optimized for efficiency and power density. Makes use of a three-phase arrangement to more evenly distribute power and reduce the strain on individual parts. The configuration assists in increasing the performance of total converter along with managing high power levels. Implements soft-switching strategies to drive up efficiency and slash switching losses.Soft switching prolongs the life and increases the dependability of switching devices by easing the strain on them.

M. H. Kheraluwala et al. [5]

The paper "Design Considerations for High Power Density DC/DC Converters" by M. H. Kheraluwala and D. M. Divan discusses critical aspects of designing DC/DC converters with a focus on achieving high power density. The authors address several key design elements, including thermal management, electromagnetic interference (EMI) mitigation, and efficiency optimization. They also emphasize the importance of component selection, circuit topology, and packaging techniques to enhance power density. The paper provides both theoretical insights and practical guidelines, making it a valuable resource for engineers developing high-performance DC/DC converters for applications such as renewable energy systems and electric vehicles.

D. Xu et al. [6]

To be specific, this paper principally develops a hybrid control scheme that cojointly governs phase-shift and pulse-width modulation (PWM) of bidirectional DC-DC converters. ZVS is thereby realized by both the directions of operation, which certainly results in lower switching losses but with an increased performance from converter side. Numerical analysis and experimental results are presented by the authors which elucidate that the suggested control scheme can effectively mitigate current disturbance with improved overall reliability and performance of a converter within different application range.

H. Bai et al. [7]

An experimental study on control methods of isolated bidirectional DC-DC converters is demonstrated. Citing methods including phase-shift control (common practice), dual-phase-shift control, and a model-based approach, the authors offer their findings. They find that model-based control offers the best efficiency and dynamic response, while dual-phase-shift control strikes a good balance between complexity (and therefore cost) &. improvment in performance over traditional phase shift controlled systems.

G. D. Demetriades et al. [8]

The study aimed to characterize and enhance the performance of these converters, pivotal in high efficiency power conversion applications. A comprehensive small-signal model is derived for active bridge models, including the single- and dual-active bridge. These models are needed to analyze the dynamical behavior and develop proper control strategies. Furthermore, the author also discuss about operation principle and control challenge of SAB topolog with small-signal models that will enable a better understanding on how parameters help or degrade its performance. He also specifically concentrating on the DAB topology, which is widely employed due to its high efficiency and ability of bidirectional power flow deployment thorough detailed small-signal systems developed for analyzing dynamic behavior in different operation modes. The paper presents several SAB and DAB converter control strategies proposed by the author. Stability,fast dynamic response and efficiency take precedence. Expertise in phase-shift control and advanced modulation techniques are discussed depth wise. For this, it compares and evaluates the power density of single versus dual active bridge topologies as well their control complexity efficiency. This has outlined the usefulness of each topology for different applications and its pros / cons. Numerous experimental work has been carried out and they provide substantial validations for the control strategies as well as small-signal models. These tow results can be used in the design of electric vehicles, energy storage systems and various other high-efficiency power conversion applications due to its low conduction loss than driving under different locking time. Besides, strong control methods are important to keep the effectiveness for different load and input conditions. Comprehensive small-signal models and effective control schemes for single and dual active bridge converters are proposed in the thesis, of great significance to research community working on power electronics. This is a way to improve dynamics and efficiency of such converters. This better situates them for application in modern power conversion applications applications. This work is essential for anyone working, either as a researcher or engineer, with high efficiency DC-DC converters due to the complete analysis and experimental validation.

R. W. Erickson et al. [9]

R.W. Erickson discusses PWM rectifiers in detail including the concepts, workings and applications of Pulse-width modulated (PWM) rectifier in chapter 20 titled "PWM Rectifiers" from his book Fundamentals of Power Electronics. These rectifiers are the crucial components of modern power electronics, to convert Alternating Current (AC) into Direct current with very high efficiency, least harmonic distortion and improved power factor. Turn on and off the switches in a PWM rectifier configuration results modify an input wave current into sine form with its correct phase angle. The switches control the duty cycle, in order to hold/adjust the voltage and current output. The operation modes of continuous and discontinuous conduction are described. For lower-power and easier control, users can also make use of the Discontinuous mode function however Continuous Mode is generally desired for higher efficiency and looser output current ripple. It also addresses Various types of control like average current, voltage mode and current mode controls with the significance on low input currents total harmonic distortion (THD)and high power factor. Instead of conventional rectifiers, with PWM rectifier as shown in Fig 1 this becomes a solution to attenuate the input current harmonics. The paper goes on to discuss methods for harmonic reduction and meeting global standards (e.g. IEEE & IEC)

Variable Frequency Drive Power Factor Correction (PFC)

Describes how power factor correction is performed directly by PWM rectifiers to increase the overall stability and performance of a power system. By literally ensuring that the input current and voltage are in SYNC, PFC circuits reduce reactive power, increasing overall POWER QUALITY. This is the subject of how to design PWM rectifiers for different applications and power levels. Common uses are electric vehicle chargers, renewable energy system like solar invertres/wind turbines systems, industrial power supplies and telecommunication power supplies applications. PWM rectifiers have the advantage over traditional direct converters in such aspects as better efficiency, power factor and compact properties.

Covers concerns like the need of advanced semiconductor devices, deployment (cost) and control algorithms intricacy. This topic is discussed in greater detail on the PWM rectifiers page in Fundamentals of Power Electronics. For this reason, the use of these rectifiers is important for modern power conversion systems with high-power quality and efficiency. Readers will be enabled to design PWM rectifiers for high-performance application using this book.

Z. Guo et al. [10]

In this study, a new modulation scheme for dual active bridge (DAB) converters is suggested and implemented such that smooths the modes transitions are achieved increasing carefully in various performance factors like ZVS loss trade-off with conduction losses. Specifically, this modulation scheme enables the discovery of an ideal switching ordering that obtains zero-voltage-switching (ZVS) and low conduction loss under multiple operating modes without reconfiguring gate driver circuit. The main contributions in this paper are -No performance degradation during mode transitions: the developed new modulation scheme guarantees that modes transition seamlessly without any performance loss; Balanced ZVS with conduction loss : optimising an important trade-off, which is between ZVS and conduction losses, since two conflicting goals can achieve by a same gate driver configuration. Experimental demonstration via a 1.2 kW practical prototype Verbesserung der Leistung Link. Such a method is applicable for low-voltage high-frequency applications where greater efficiency and flexibility are required, such as battery management systems (BMS) or renewable energy sources; it proposes to overcome the limitations of traditional modulation techniques by introducing closed-loop control strategies together with new mode-switching mechanisms.

Tan et al. [11]

The Digital Active Bridge (DAB) converter is studied extensively by Tan et al. for high power applications with phase shift modulation in their paper [1]. The work brings out the importance of phase-shift modulation for improving DAB APSs. The capability of the proposed modulation technique is provided in terms how it can improve power conversion efficiency and to control flexibly on electrical power flow. The paper provides a complete review of the DAB converter working-condition performance,vertically for efficiency and power density also horizontally thermal aspects. Looking at this and related data informs how the advanced phase shift modulation carries out with regards to these factors.

This work is especially important with respect to high-power applications, supplying the design considerations and operational schemes needed in order that DAB converters can be featured more prominently within similar contexts. In comparison with other reports that have mostly presented comprehensive details of the application to converters cascaded after DAB, this study investigates in detail on phase-shift modulation and therefore will be useful for engineers and researchers engaging high-power DC-DC conversion systems.

Gupta et al. [12]

A study on efficiency, power density and control complexity performance comparison between DAB and PSFB converters is presented in the paper. This paper also sheds the light on how converters can be different in operation and their specific advantages over each other, to help make a better design choice while making converter for an application. The paper argues about the appropriateness of different converter types to specific activity domains and proposes practical recommendations from performance metrics. The comparative study is important for selecting proper converter topologies within different applications by engineers and researchers where it clearly indicates trade-offs versus benefits between DAB Vs. PSFB converters.

Su et al. [13]

Su, Lai & Chiang (2014) detailed a comparison of dual active bridge (DAB) converters using phase-shift modulation for performance evaluation. In this paper, a comprehensive analysis is given to examine efficiency and power handling capability of DAB sources under phase-shift modulation in-depth. The video above examines the effect of modulation on converter performance, along with efficiency improvements and stable considerations. The results of this study are crucial for a better insight into operational advantages given by the phase-shift modulation in DAB converters, which provides important guidelines to be used at converter design and performance optimization.

Lee et al. [14]

This paper presents advanced design strategies for the Dual Active Bridge (DAB) converters to operate at high efficiency without compromising their performance. The paper introduces new design techniques that upgrade DAB converters efficiency thanks to the optimization of those components and control schemes. Significant elements include comprehensive design improvements and how these have been integrated to enhance converter performance; specifically efficiency and cool running. The study presents specific principles-of-design and demonstrates the applicability of these novel methods on several examples with a lar- ge number of simulation results as well as microcontroller-based applications.

Lee et al. [15]

This paper discusses the detailed design and analysis of Dual Active Bridge (DAB) converters suitable for high-power applications This paper covers a range of design considerations and optimization Techniques To Improve the performance Of DAB converters in high power applications. This report takes a deeper dive into clinch technology, looking at component choice (including electronic devices), thermal management and control techniques. The research paper presents theoretical perspectives, simulation outcomes as well as practical design guidelines that exhibit the potential of reliable and efficient operation in high-power operating conditions.

Xu et al. [16]

This paper investigates the control and design considerations of Dual Active Bridge (DAB) converters for high-power DC-DC applications. The paper discusses state-of-the-art control techniques and design rules for improving the performance and efficiency of DAB converters proposed in high-power applications. They conduct thorough mechanisms of control algorithms and design parameters which affect the stability performance, operational efficiency, etc., to demonstrate what should be improved. The study provides practical insight on performance enhancement of DAB converters in hard switched applications through simulations and design examples.

Jain et al. [17]

In this paper, the modeling and various design considerations for high frequency Dual Active Bridge (DAB) converters are presented. This paper examines the issues and techniques involving high-frequency operation from an efficiency, component selection, and thermal standpoint. The authors follow with a uniform model of high-speed links and shared principles behind practical design examples. They set out to maximize DAB converters performance for high-frequency operation applications.

Li et al. [18]

This article does a detailed review of Dual Active Bridge (DAB) converter topologies and control strategies. The paper provides a systematical evaluation of different DAB converter design and compares their operation principle, advantages as well disadvantages. It spans a variety of topologies and control strategies, detailing their performance characteristics as well as applications. The state-of-the-art and recent advances in DAB converter technology are discussed in addition to the major developments, leading readers from a basic understanding of the operation principles through extensive practical results implementation for various applications.

Yang et al. [19]

This investigates the control strategy of Dual Active Bridge (DAB) DC-DC converters employed for efficient power conversion. The paper is dedicated to the implementation of advanced control techniques aimed at increasing performance and efficiency, specifically for DAB converters. It provides different control techniques which were applied and analyzed their influence on the converters operation for increased efficiency, stability in addition to dynamic response. Their study provides valuable insights into optimizing control methods for better performance in practical applications.

Mattavelli et al. [20]

This paper focuses on the design and implementation of a Dual Active Bridge (DAB) DC-DC converter for electric vehicle (EV) application. The paper outlines what design aspects are required to maximize the DAB converter performance in EV applications and electric power systems. Specifically, the authors tackle efficiency, thermal management and control strategies for EV applications. Experience from practical implementation and experimental results are presented in the study to obtain a direction of using this converter that could result increases performance and reliability of electric vehicle power systems.

De et al. [21]

Focuses on the analysis and design of Dual Active Bridge (DAB) converters specifically for high-voltage applications. Takes an in-depth look at design considerations and performance attributes for employing DAB converters up to high-voltage. Challenges and workarounds of high-voltage operation including component selection / design, voltage stress management are nicely presented. The study provides useful guidance regarding how to enhance the reliability and efficiency of DAB converters for high-voltage applications as well through theoretical analysis, and design examples.

Liu et al. [22]

It deals with enhanced control techniques to improve performance of Dual Active Bridge (DAB) converters. This paper studies different control schemes to improve the efficiency and dynamics of DAB converters. Converter Performance Metrics The authors evaluate the effect of these controls on converter performance metrics, such as efficiency, stability and transient response. The study performs a theoretical analysis, simulations and an experimental verification to offer practical guidelines for the optimization of DAB converters with improved performance across application spectra.

Li et al. [23]

The study of Li et al. (2019) introduce a single-phase shift control strategy of the dual active bridge (DAB) converters for photovoltaic (PV) applications, providing an in-depth investigation on its performance and benefits. High-power PV applications are particularly addressed with reference to power transfer efficiency and losses, however the authors pay no attention whatsoever to system level expectations or requirements. Developed algorithms for Modeling and Control to optimize the stability of DAB converter in action. Li et al. demonstrate - through both simulations and experiments- that their approach improves the conventional method in dynamic response as well as load-tracking performance. The results of this work could give a good support for the design process toward adoption high efficiency power conversion as an applicable solution to rise up DAB performance in handling PV systems, which is one kind of most available and distributed energy source.

Zhou et al. [24]

Zhou et al. analyze and optimize the single-phase-shift control of dual active bridge (DAB) converters for photovoltaic PV applications, focusing on efficiency performance (Properties). In this way, both issues are discussed by the authors and an in-depth theoretical model as well as some pragmatic optimization methodologies for improving operating performance of DAB converters is presented. Zhou et al. simulated and experimentally verified their work on human subjects), which corroborate the power losses reduction and dynamical performance gain that can be made possible with this control optimization scheme Results in perception showed a technically excellent increase converter behavior, for example indicating good realization of reliability; hence it serves potential new ideas to evolve further input-wise coordinated photovoltaic power conversion systems. This work forms the basis for a further improvement in renewable energy systems based DAB converter technologies and is an essential contribution to this literature.

Yang et al. [25]

Yang et al. low-voltage high-power single-phase shift-controlled dual active bridge (DAB) converter for photo voltaic applications. The authors investigate the enhancement of power density and efficiency for DAB converters, which was important especially in connection to power conversion via photovoltaic systems. This, combined with advances in control strategies and design optimization, considerably improved the reliability of diode converter under unsymmetrical operation. provide improvements of upto three orders-of-magnitude in efficiency as well power density. Such a system, able to work in high-power mode be as stable with efficiency is desired according the experiments. This important research, enabled by the ShanghaiNet Foundation, provides essential evidence and feasible techniques for popularizing DAB convertion technology into current renewable energy system applications advancing a future with more efficient solar power.

Xu et al. [26]

This paper gives a performance analysis to the single-phase shift control in DAB converters, when employed particularly for photovoltaic (PV) applications. Authors provided an in-depth overview toward converter efficiency-based analysis associated with power handling and dynamic response of the single-phase shift controller. The experimental results show that the proposed DAB converter under single-phase shift control can significantly enhance the performance of a traditional DAB system, and obtain near-optimal operation at optimal power transfer minimal losses condition. In this paper, the method proposed by Xu et al. is recommended as an outstanding approach to improving power processing performance in PV systems through detailed simulation and practical test results. In conclusion, this work may help the research and development of future power conversion technology in renewable energy system for more efficiency or reliability.

Liu et al. [27]

The paper discusses a detailed study of advanced DAB converter topologies and control schemes to improve their efficiency, applied Renewable Energy System. By performing thorough simulations and experiments, they show that their strategies can achieve significant improvements in power conversion efficiency and system reliability. Liu et al. focuses on some primary obstacles, such as the power losses and dynamic response. provide key perspectives on next-generation DAB reforming for power-to-fuel. This will be a significant step toward power electronics in green/power system applications.

Wang et al. [28]

In this paper by , it proposes improved modulation methods of DAB SoC dynamic capability, and is published in IEEE Trans Power Electron 2013. In this article, different modulation schemes have been evaluated and concluded to be the most adequate for transient response and proper overall performance of DAB converters in dynamic conditions, using both detailed modeling and experimental validation to estimate the optimal control region. demonstrate that their proposed techniques can significantly enhance the stability and performance of DAB converters against fast-changing load/source voltage excitations. Additionally, the results provide valuable insight which is useful to enhance converter performance as well contribute towards more agile and reliable power conversion systems.

Zhang et al. [29]

In 2015, Wang et. Salazar et al proposed a new paper to be published in IEEE Transactions on Power Electronics concerning the dynamic modeling and control of dual active bridge (DAB) converters for grid-tied applications. The authors of this work have dealt with the DAB converters performance improvement when connected to grid-connected systems Combining these aspects together, they present a comprehensive dynamic model and are trying to derive efficient control strategy. Their research is a mixture between theoretical learning and its application on systems, which verify the capability grid-compatible of their proposed-control strategies with an enhanced response performances for the power converters. Zhang et al. using large number of simulations and experimental results, show that their strategy is capable of reaching it in grid-tied applications with high reliability for power conversion / operation. The paper lists out different strategies pertaining to the controller implemented in power electronics, which would be very beneficial for future enhancement of renewable energy integration.

Lee et al. [30]

They compared different control strategies to exert influence on the behavior and efficiency of DAB converters, which were published in IEEE Transactions on Industrial Electronics (2017) The advantages of the introduction to some techniques like phase shift control and a variety model-based encoder scheme are explained from Lee et al. in hybrid excitation machines with respect Min, J.s., however contrasted benefits among methods are detailed. This combines nicely with the more intuitive understanding that converters are operated differently when controlled otherwise specifically showed through the full analysis, both simulated and experimentally verified. This contribution is fundamental to shed light over some of the phenomena present in DAB converters and can be exploited for understanding why certain con trol strategies tend do be less or more effective depending on which particular industrial application they apply.

Rodríguez Alonso et al. [31]

The works presented in (2021) give a neat study on the dual active bridge (DAB) converters for bidirectional DC/DC conversion. We then delve deeper into the design, operation and performance characteristics of DAB converters illustrating the suitability of a specific type in bidirectional power transfer for many application contexts. Rodríguez Alonso et al. [19] addressed this issue with a comprehensive study of various topologies and control strategies; demonstrate how DAB converters can operate to efficiently control power flow in both directions, optimize performance-related parameters such as efficiency and dynamic response. This work provides a useful reference for future research on DAB converters from both ease of realization and optimized performance aspects in bidirectional power conversion systems.

2.2. Motivation and Objective of the Present Work

The rapid development of renewable energy resources, including photovoltaic (PV) systems requires effective and reliable power conversion technologies. Of these, the DAB converter is considered suitable for high-power applications as it has advantages such bi-directional power flow ability, potential galvanic isolation and higher efficiency. Especially the Single Phase-Shift(SPS) modulation strategy provides simpler control method which is attractive for DAB converter in PV applications.

Key Motivations:

The SPS modulation strategy allows to achieve an easy control solution, enabling a very simple DAB converter design. Bridges of the primary and secondary may have their phase angle varied to controlled power transfer, enabling adjustment to compensate for changes in PV output as well as load demand.

In PV systems, galvanic isolation is very important to prevent problems related ground faults and resulting in the powers of both equipment / individuals. Isolation is provided by the high-frequency transformer in the case of DAB converter thereby adding to reliability and safety during power conversion process.

To improve the efficiency of DAB converter it is important to be able know how power transfer, phase angle and switching frequency are related and what control can be done on each. The intent of this work is to determine the optimal conditions for power versus phase angle and switching frequency with in PV systems

Objectives:

1. Study the relationship between power transfer and phase shift in a DAB converter to optimize power transfer during different operating conditions.

2. Investigation of how different switching frequencies affect the performance of the converter.

3. Create detailed performance maps power vs. phase angle for different phase angles and switching frequencies to understand the behaviour of the converter under varying operating conditions

2.3. Layout of the Thesis

Chapter I: Introduction

Chapter II: Literature review

Chapter III: Single Phase-Shift High Power DAB – MATLAB Model Design for PV application.

Chapter IV: Calculations and Results

Chapter V: Conclusion

CHAPTER – III

Single Phase-Shift High Power DAB – MATLAB Model Design for PV application

3.1. Introduction

The performance and efficiency of High Power Dual Active Bridge converters are heavily influenced by the choice of control strategy. Single Phase Shift Modulation offers simplicity and effectiveness for many applications, while Dual and Triple Phase Shift Modulation provide enhanced control and efficiency under varying conditions. Hybrid modulation techniques and advanced predictive and adaptive controls offer further improvements in performance and reliability. Resonant and soft-switching techniques address the challenges of switching losses and EMI. The ongoing development and refinement of these control strategies are critical to the continued advancement of DAB converters in high-power applications.

In this thesis paper, we will study about the Single-Phase Shift Modulation (SPSM) control strategy with the help of simulation and mathematical calculations.

Rectangular transformer voltages V_p and V_s with switching frequency f_{sw} and phase shift φ are applied to the transformer and the converter inductance L for phase shift operation. The power transferred is regulated by the phase shift angle φ.

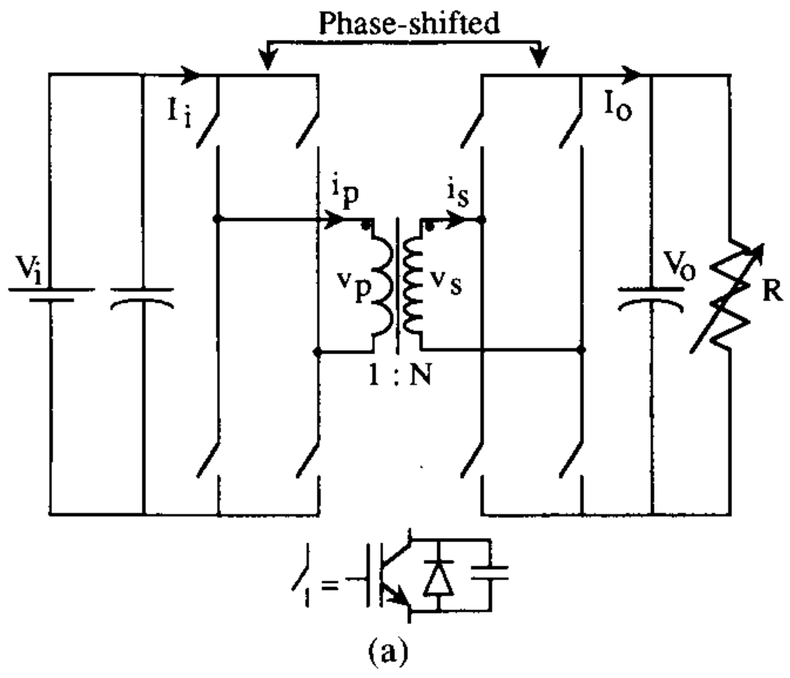


Fig. 5. Circuit schematic of single phase Dual Active Bridge DC-DC Converter [1]

Effects of Phase Shift on Output Voltage Regulation

Phase shifting at Dual Active Bridge (DAB) Converter: The DAB converter is highly dependent on phase shift, for the accurate stabilization of output voltage. In the DAB converter power transfer is happened by introducing a phase shift between the leading and lagging bridges. The DAB converter can be controlled at its full operating range using the different phase shift modulation techniques.

Phase Shift Impact on the Power Transfer Capability

In a DAB converter, the transfer capability is greatly influenced by phase shift between leading and lagging bridges. It is also necessary to uniformly zero-voltage-switch (ZVS) over full ZVS range, by using asymmetric and dual phase shift modulation strategy. Furthermore, a triple phase shift control is used in order to reach the highest efficiency by controlling both power transfer and reactive currents. The direction of power flow can also be easily reversed by adjusting the phase shift between the two bridges

The impact of Phase Shift on System Stability

In DAB converter, the Phase shift angle significantly affects the whole system's stability. The stable operation can be kept by limiting the phase shift angle to operate in a stable region without getting back into an unstable one. Therefore, the use of model-based single-phase shift control can increase voltage stability, particularly when pulse power loads.

3.2. MATLAB Model OF Phase-Shifted High-Power DAB Converter for PV Application (using PV Array)

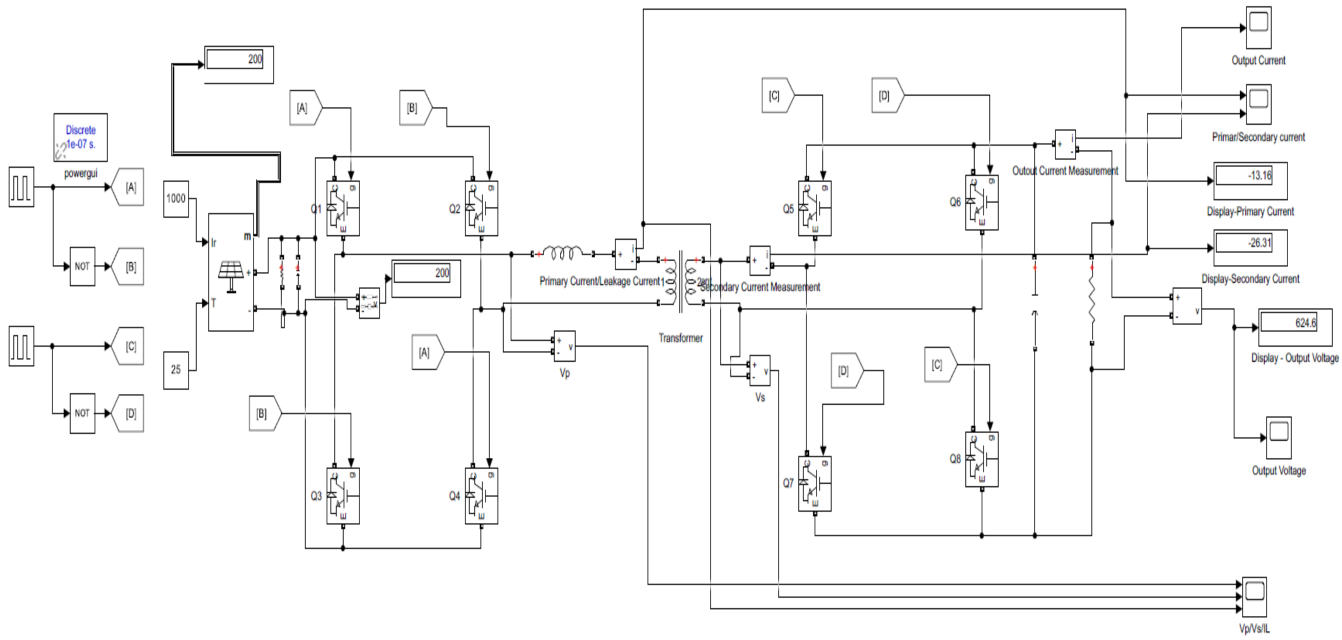


Fig 6. MATLAB Model of Phase-Shifted High-Power DAB Converter (PV Array)

3.3. PV Array specifications

Model	**Irradiance (W/m^2)**	**Temp. (^0C)**
SunPower SPR-295E-WHT-D	1000	25

Table.1: PV Array Specifications

3.4. Role of each component in a DAB Converter

In a dual active bridge (DAB) converter, each component plays a crucial role in ensuring the efficient and reliable transfer of power. Here's an overview of the functions of the key components: inductor, capacitor, resistance, IGBT diode, and transformer.

Inductor

Role:

Energy Storage: The inductor stores energy in its magnetic field when current flows through it.

Current Smoothing: It smooths out the current flow, reducing ripple and noise.

Control of Power Flow: In the DAB converter, the inductor works with the transformer leakage inductance to control the transfer of power between the primary and secondary sides. It helps manage the phase shift control strategy by determining the power transfer rate and dynamics.

Capacitor

Role:

Energy Storage: Capacitors store electrical energy in an electric field, providing a reservoir of charge.

Voltage Smoothing: They filter and smooth out voltage fluctuations, reducing ripple and noise in the output voltage.

Decoupling: Capacitors decouple AC signals from DC power supply, helping to stabilize the voltage levels in the converter circuits.

Resonance Management: Capacitors can also form resonant circuits with inductors, which are used to optimize switching performance and efficiency.

Resistance

Role:

Damping: Resistances provide damping in the circuit, preventing oscillations and improving stability.

Power Dissipation: They dissipate energy as heat, which is useful for controlling transient responses and limiting current surges.

Load Representation: In practical circuits, resistances represent the load connected to the converter, affecting the overall performance and efficiency.

IGBT (Insulated Gate Bipolar Transistor) and Diode

Role of IGBT:

Switching: IGBTs act as switches in the converter, rapidly turning on and off to control the flow of current through the circuit.

High Efficiency: They provide high efficiency and fast switching speeds, which are essential for high-frequency operation in DAB converters.

Voltage and Current Handling: IGBTs can handle high voltages and currents, making them suitable for power conversion applications.

Role of Diode:

Freewheeling Path: Diodes provide a freewheeling path for current when the IGBT switches are off, allowing continuous current flow and preventing voltage spikes.

Protection: They protect the IGBTs from reverse voltage by clamping voltage spikes, ensuring the reliability and longevity of the switching devices.

Rectification: Diodes rectify AC signals, converting them to DC, which is crucial for the operation of the DAB converter.

Transformer

Role:

Voltage Level Adjustment: The transformer adjusts voltage levels between the primary and secondary sides, facilitating efficient power transfer across different voltage domains.

Isolation: It provides galvanic isolation between the input and output, enhancing safety and protecting sensitive circuits from high voltage transients.

Energy Transfer: The transformer’s primary and secondary windings enable the transfer of energy, with the phase shift between the primary and secondary switches controlling the direction and magnitude of power flow.

Leakage Inductance: The transformer's leakage inductance plays a critical role in the power transfer dynamics and is used in conjunction with external inductors to manage the phase shift control strategy.

CHAPTER – IV

Calculations and Results

Here we have considered no losses.

4.1. Calculation

The Power Flow Equation is given as,

$$P = \frac{m{V_i}^2}{X_L}\varphi\left(1 - \frac{\varphi}{\pi}\right)$$

Also, $m = \frac{V_O}{nV_i}$

And, $X_L = \omega L = 2\pi f_{sw} L$

$$\therefore \; P = \frac{V_i V_o}{2\pi f_{sw} L n}\varphi\left(1 - \frac{|\varphi|}{\pi}\right)$$

where, P → Output Power

V_i → Input Voltage

V_o → Output Voltage

φ → Phase Angle in Radians

n → Transformer Turns ratio

f_{sw} → Switching frequency

Calculation Of Phase Angle:

$$\Delta\varphi = 2\pi f_{sw} \Delta t$$

where, $\Delta\varphi$ → Phase Angle in Radians

f_{sw} → Switching frequency

Δt → time delay (value obtained through MATLAB)

4.2. Parameters for Switching Frequency (f_{sw} = 30kHz)

Parameter	**Symbol**	**Value**
Inductance	L	80μH
Capacitance	C	100μF
Resistance	R	50Ω
Switching Frequency	f_{sw}	30 kHz
Transformer Turns Ratio	n	2:1
Duty Cycle	d	50%

Table 2: List of parameters and their values (30kHz)

4.2.1. MATLAB simulation Results (for φ = 90^0, f_{sw} = 30kHz):

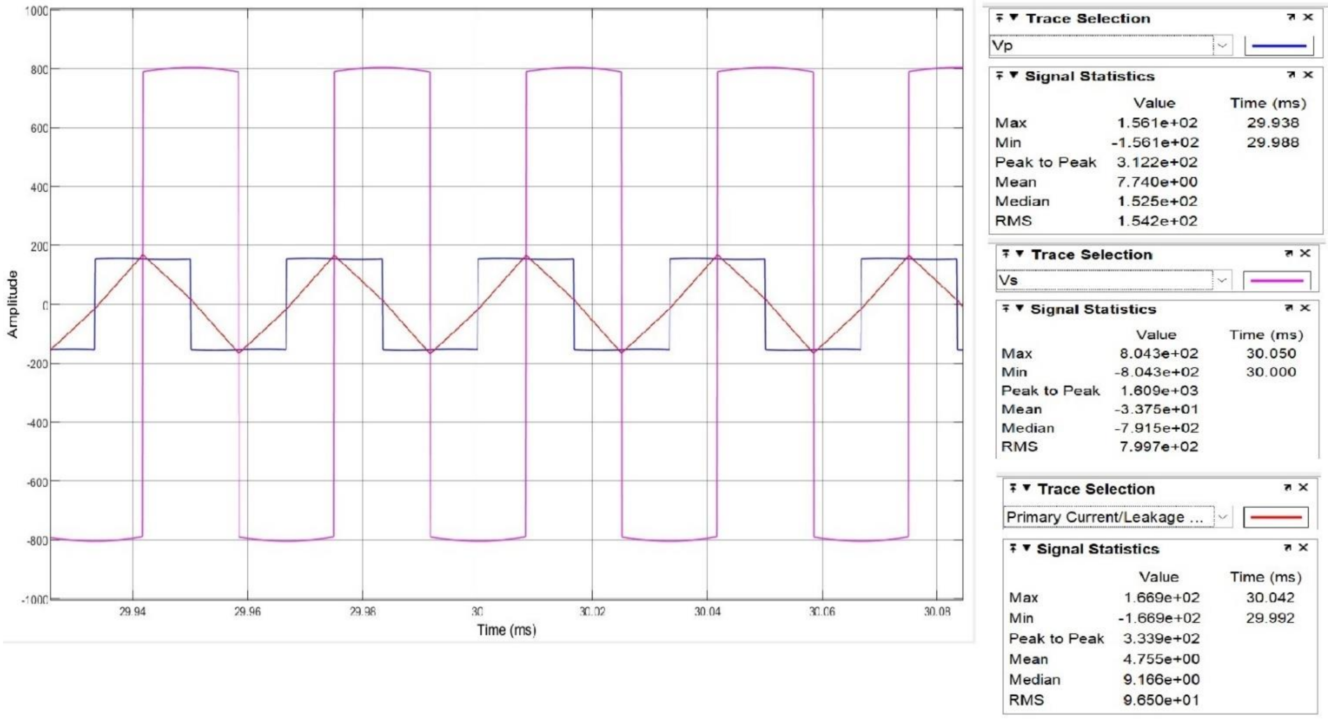


Fig 7.a. Primary Voltage, Secondary Voltage, Leakage Current (30kHz)

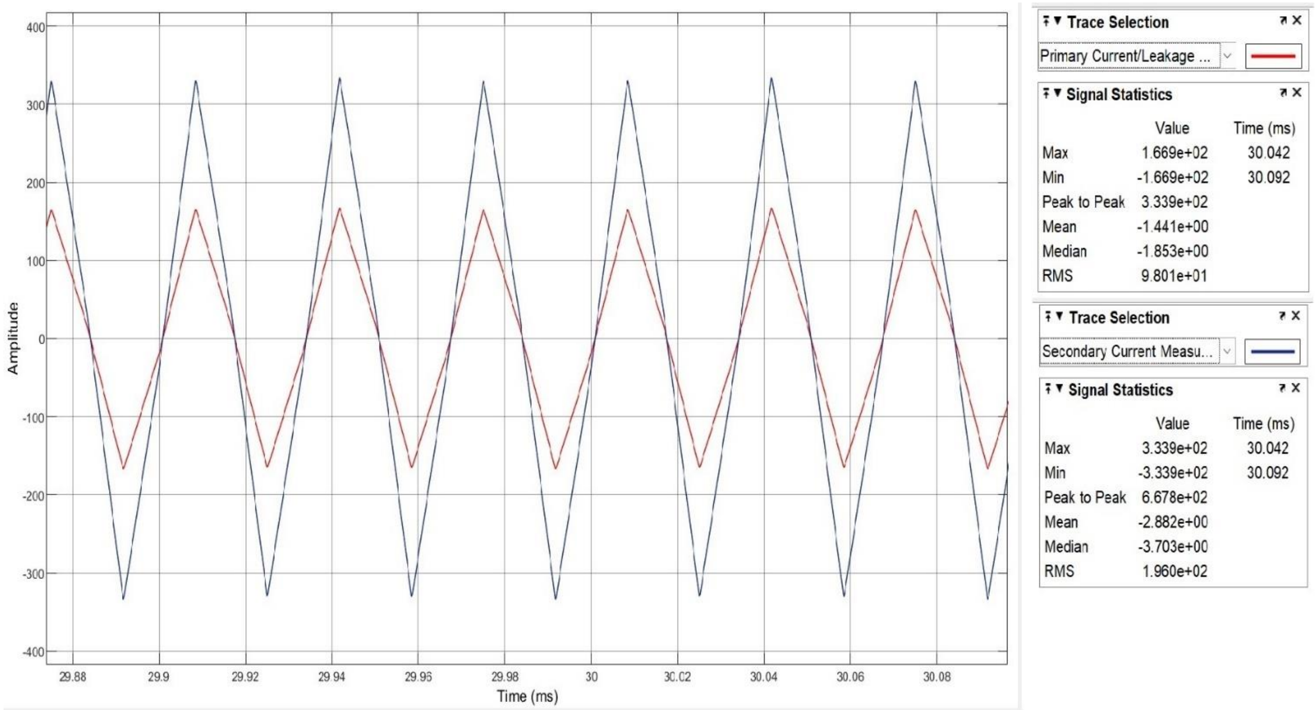


Fig 7.b. Primary Current and Secondary Current (30kHz)

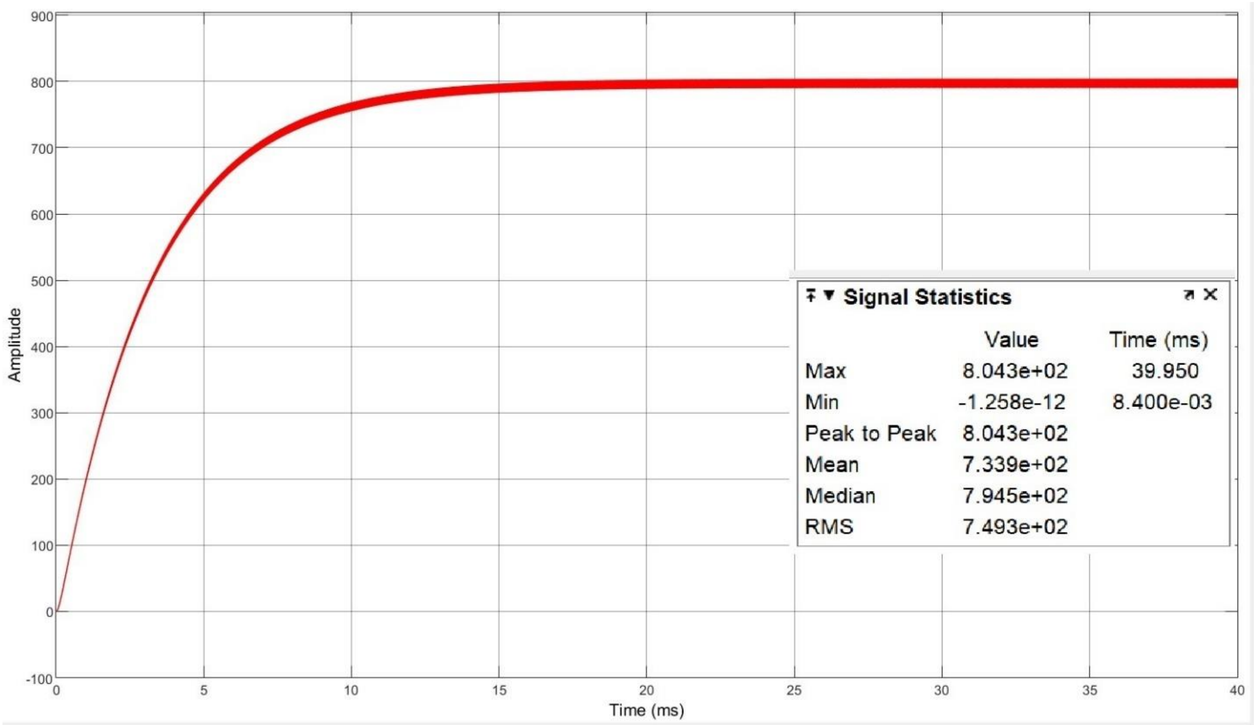


Fig 7.c. Output Voltage (30kHz)

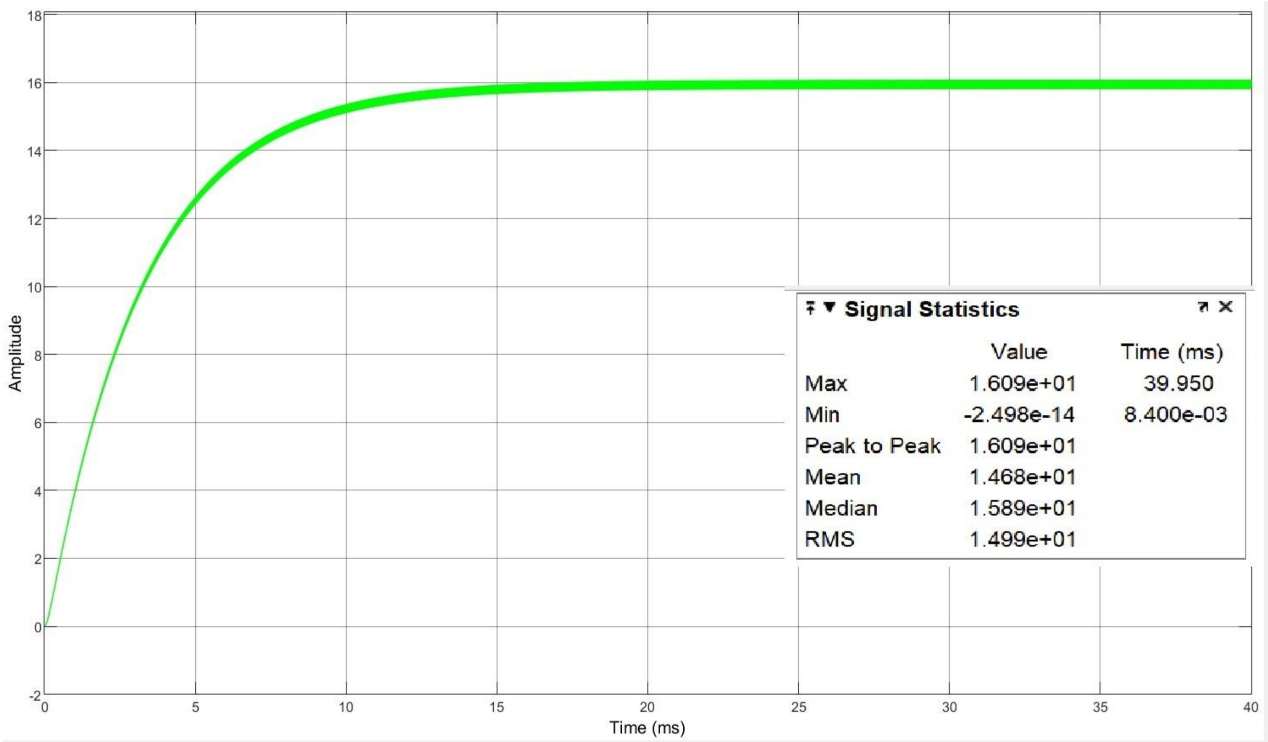


Fig 7.d. Output Current (30kHz)

4.2.2. Table for Output Voltage, Output Power, Output Current (When Switching Frequency (f_{sw}) is 30kHz):

Δϕ (rad)	Δϕ (deg)	f (sw) (Hertz)	L (Henry)	n (Turns Ratio)	PV Vin/Vp (Volt)	Vs (Volt)	Vo (Volt)	I lk (Ampere)	Po (Watt)	Io (Ampere)
0	0	30000	0.00008	2	240.6	0	0	24.88	0	0
0.261788916	15	30000	0.00008	2	229.8	364.6	365.1	55.7	667.5826247	7.303
0.523609248	30	30000	0.00008	2	207.3	595	595.4	10.92	1785.711731	11.91
0.785398164	45	30000	0.00008	2	185.5	714.4	714.6	138.9	2589.029298	14.29
1.047187079	60	30000	0.00008	2	168.8	772.9	773	154.8	3020.410823	15.46
1.309007411	75	30000	0.00008	2	159.1	797.7	797.7	163	3213.254198	15.95
1.570796327	90	30000	0.00008	2	156.1	804.3	804.3	16.69	3269.563281	16.09
1.832585243	105	30000	0.00008	2	159.4	797.4	797.4	168.2	3218.102407	15.95
2.094405575	120	30000	0.00008	2	169.2	772.1	772.1	166	3024.043212	15.44
2.356194491	135	30000	0.00008	2	185.2	714.4	714.6	157.5	2584.842186	14.29
2.617983406	150	30000	0.00008	2	207.4	590.8	591.2	136.6	1773.970514	11.82
2.879803738	165	30000	0.00008	2	230.2	357.1	357.7	93.6	655.1902512	7.153
3.141592654	180	30000	0.00008	2	240.6	0	0	25.38	0	0

Table 3. Output Voltage, Output Power, Output Current (30kHz)

4.2.3. Graph for Output Power Vs Phase Angle (deg.) (30kHz)

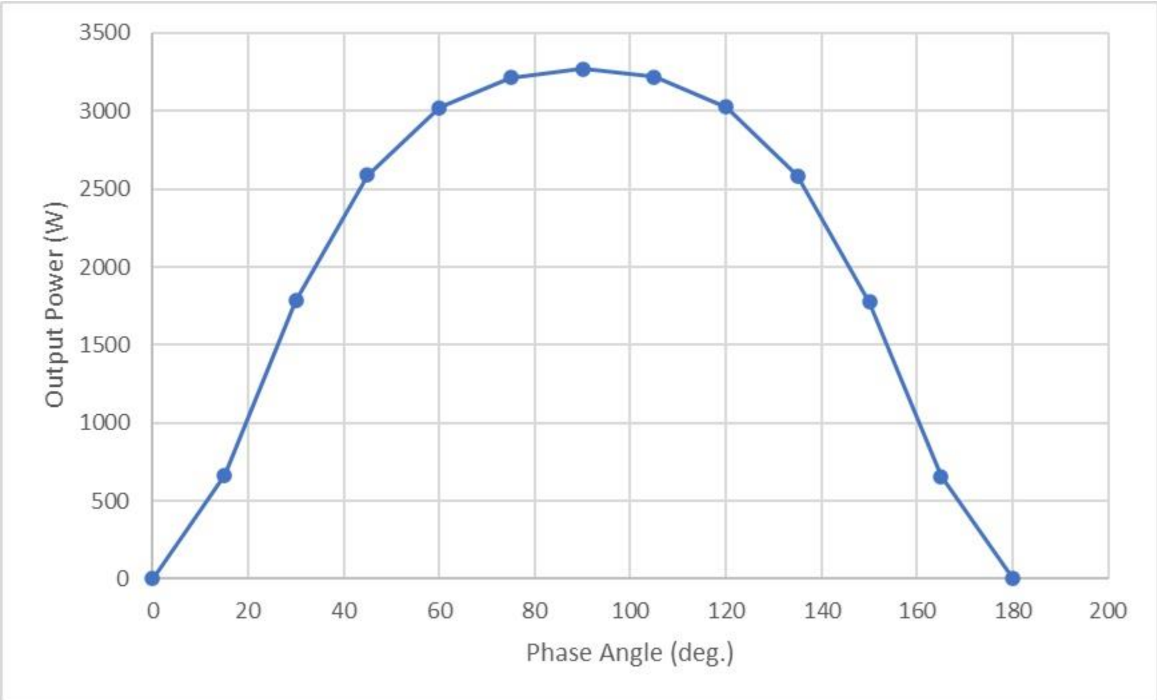


Fig 7.e. Output Power Vs Phase Angle (deg.) (30kHz)

It is clear from the above data that the maximum Power is transferred when the Phase Angle is 90 degrees and that it is zero at 0 and 180 degrees.

4.3. Parameters for Switching Frequency (f_{sw} = 50kHz):

Parameter	Symbol	Value
Inductance	L	80µH
Capacitance	C	100µF
Resistance	R	50Ω
Switching Frequency	f_{sw}	50 kHz
Transformer Turns Ratio	n	2:1
Duty Cycle	d	50%

Table 4: List of parameters and their values (50kHz)

4.3.1. MATLAB simulation Results (for φ = 90^0, f_{sw} = 50kHz):

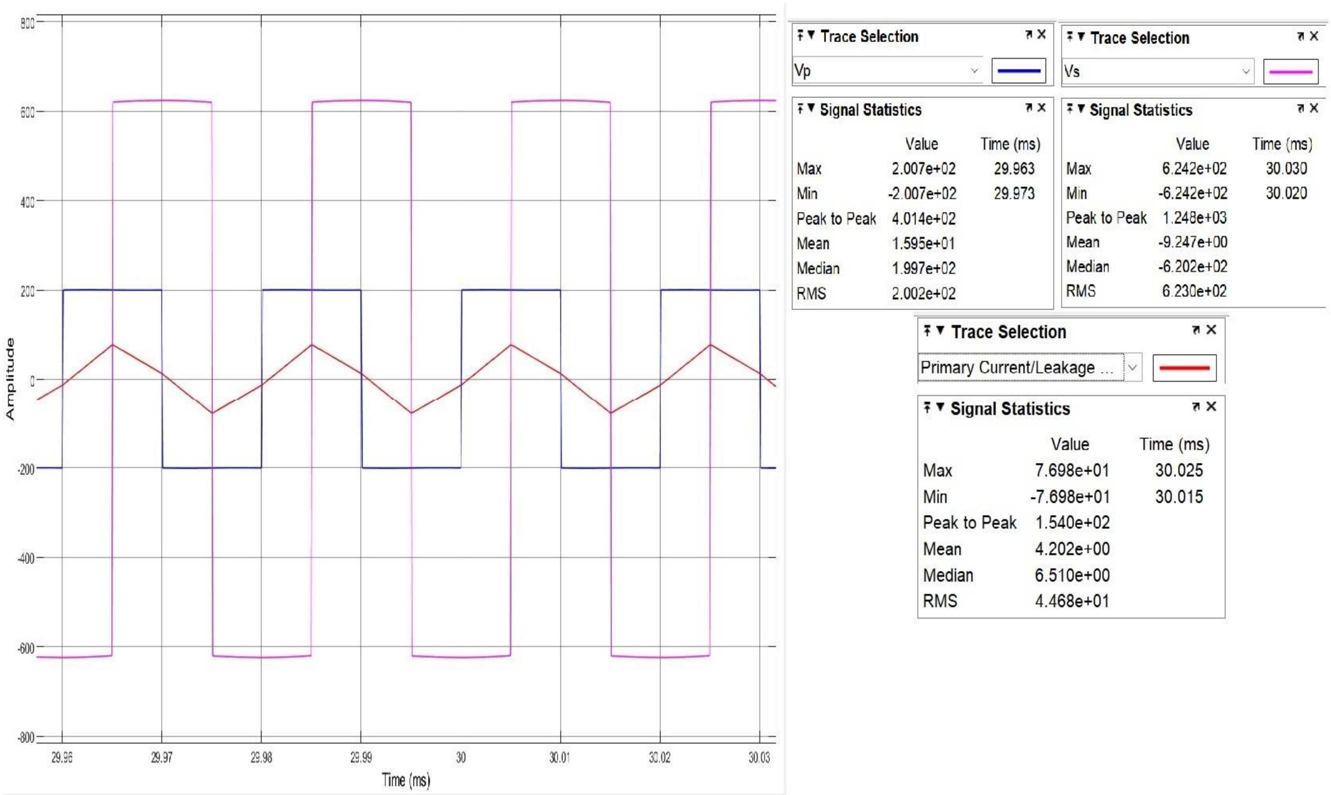


Fig 8.a. Primary Voltage, Secondary Voltage, Leakage Current (50kHz)

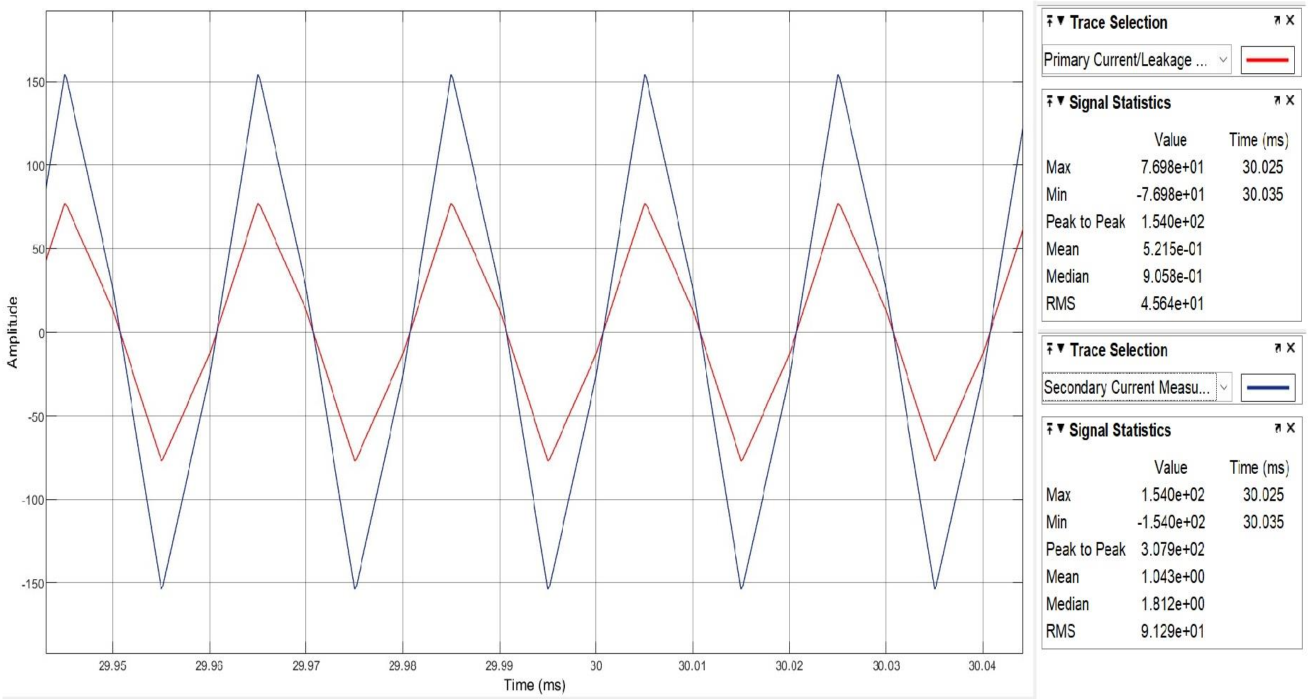


Fig 8.b. Primary Current and Secondary Current (50kHz)

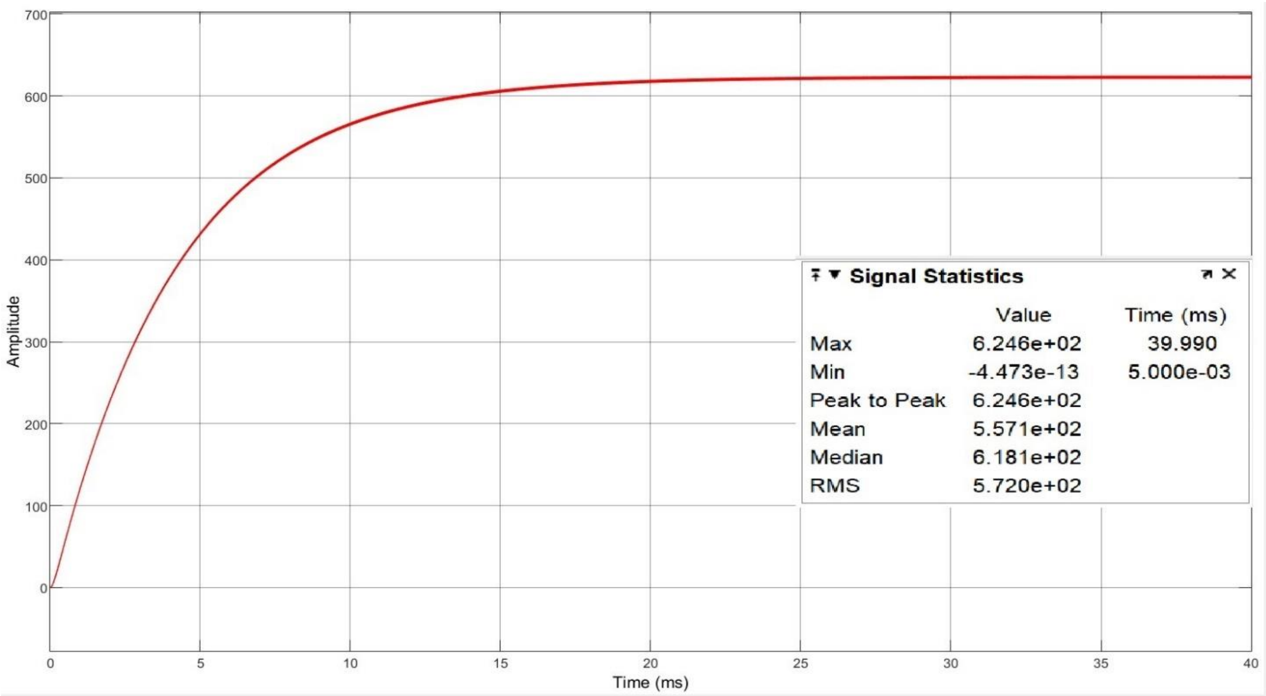


Fig 8.c. Output Voltage (50kHz)

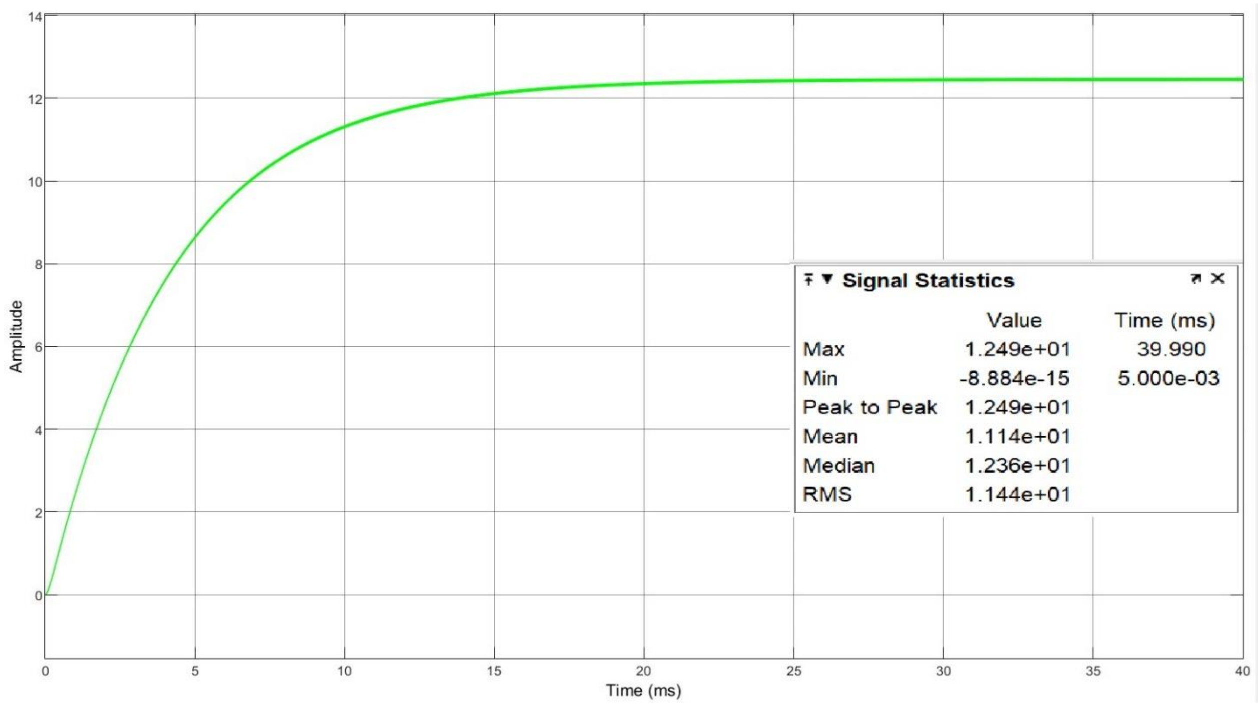


Fig 8.d. Output Current (50kHz)

4.3.2. Table for Output Voltage, Output Power, Output Current (When Switching Frequency (f_{sw}) is 50kHz):

Δϕ (rad)	Δϕ (deg)	f (sw) (Hertz)	L (Henry)	n (Turns Ratio)	PV Vin/Vp (Volt)	Vs (Volt)	Vo (Volt)	I lk (Ampere)	Po (Watt)	Io (Ampere)
0	0	50000	0.00008	2	240.4	0	0	24.65	0	0
0.261788916	15	50000	0.00008	2	235.5	239.8	240.2	17.44	270.0587992	4.804
0.523609248	30	50000	0.00008	2	226.4	396.9	397.5	39.59	781.2104162	7.95
0.785398164	45	50000	0.00008	2	216.5	504.6	505.2	55.54	1281.747657	10.1
1.047187079	60	50000	0.00008	2	207.4	579.4	579.3	67.32	1668.697489	11.59
1.309007411	75	50000	0.00008	2	202.4	613.8	613.8	73.68	1887.226189	12.28
1.570796327	90	50000	0.00008	2	200	623.7	623.6	77.01	1948.75	12.47
1.832585243	105	50000	0.00008	2	202.9	610.9	610.9	77.6	1882.949768	12.22
2.094405575	120	50000	0.00008	2	208.4	573.2	573.2	75.07	1659.08726	11.46
2.356194491	135	50000	0.00008	2	216.6	505.2	505.1	69	1282.085859	10.1
2.617983406	150	50000	0.00008	2	227.7	380.7	380.7	56.51	752.4893837	7.613
2.879803738	165	50000	0.00008	2	236.6	216.6	183.4	33.84	207.161234	4.332
3.141592654	180	50000	0.00008	2	240.4	0	0	24.87	0	0

Table 5: Output Voltage, Output Power, Output Current (50kHz)

4.3.3. Graph for Output Power Vs Phase Angle (deg.) (50kHz)

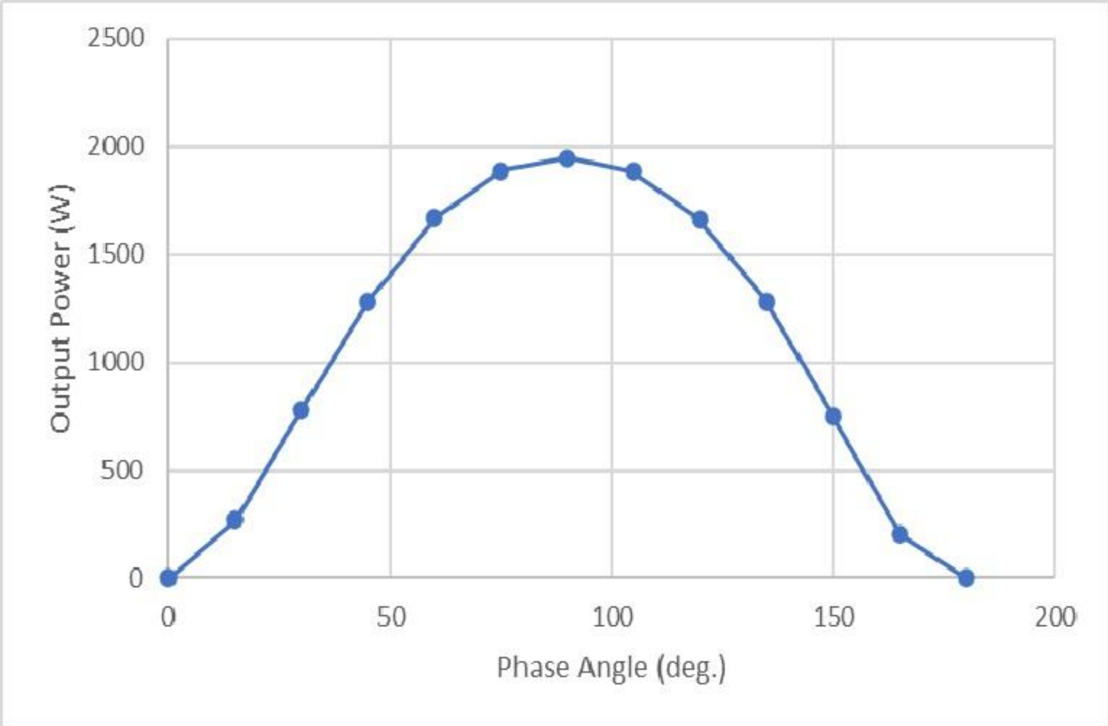


Fig. 8.e. Output Power Vs Phase Angle (deg.) (50kHz)

4.4. Parameters for Switching Frequency (f_{sw}) 75kHz:

Parameter	**Symbol**	**Value**
Inductance	L	80μH
Capacitance	C	100μF
Resistance	R	50Ω
Switching Frequency	f_{sw}	75 kHz
Transformer Turns Ratio	n	2:1
Duty Cycle	d	50%

Table 6: List of parameters and their values (75kHz)

4.4.1. MATLAB simulation Results (for φ = 90^0, f_{sw} = 75kHz):

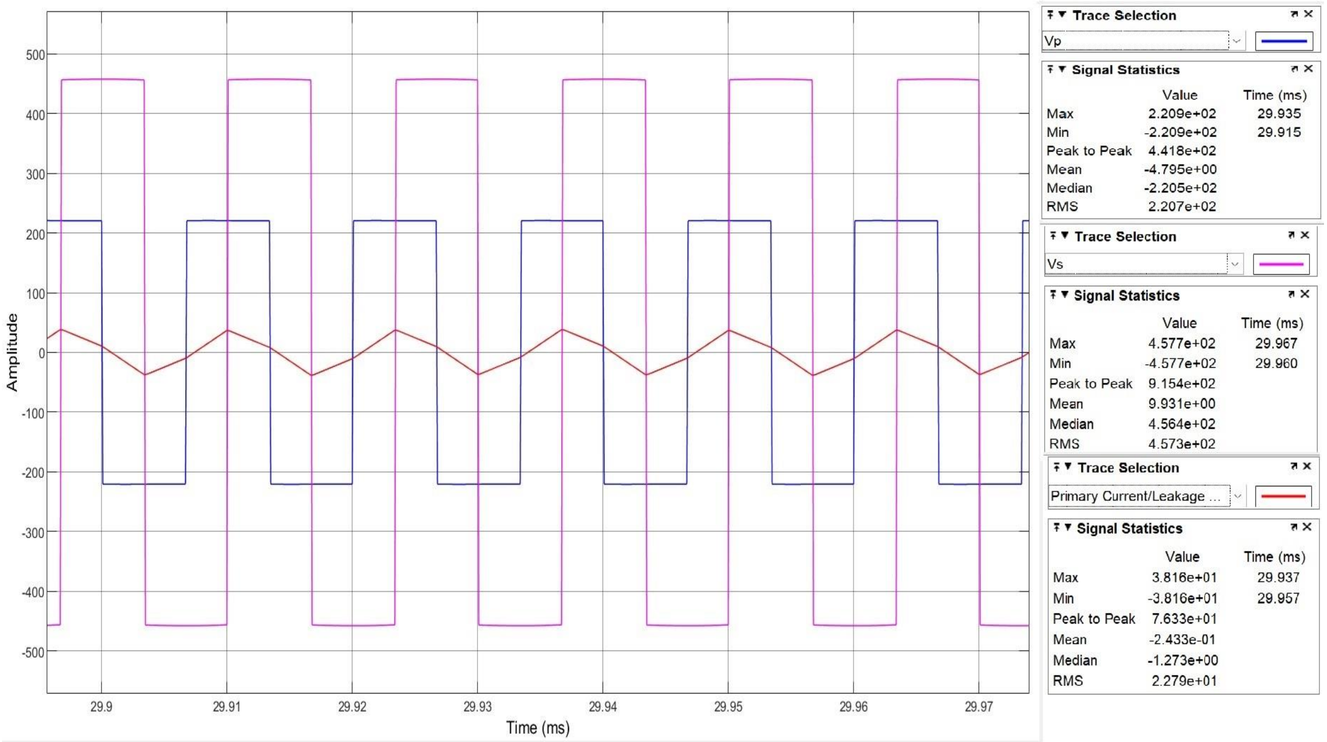


Fig. 9.a. Primary Voltage, Secondary Voltage, Leakage Current (75kHz)

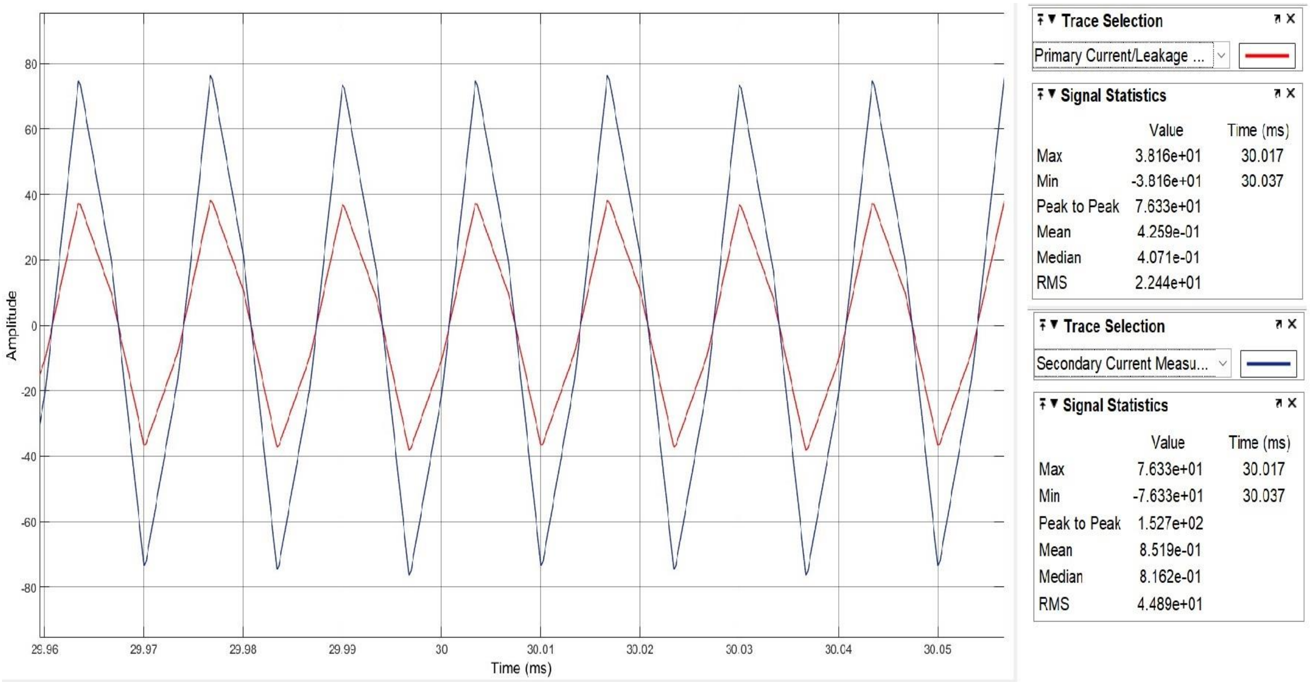


Fig. 9.b. Primary Current and Secondary Current (75kHz)

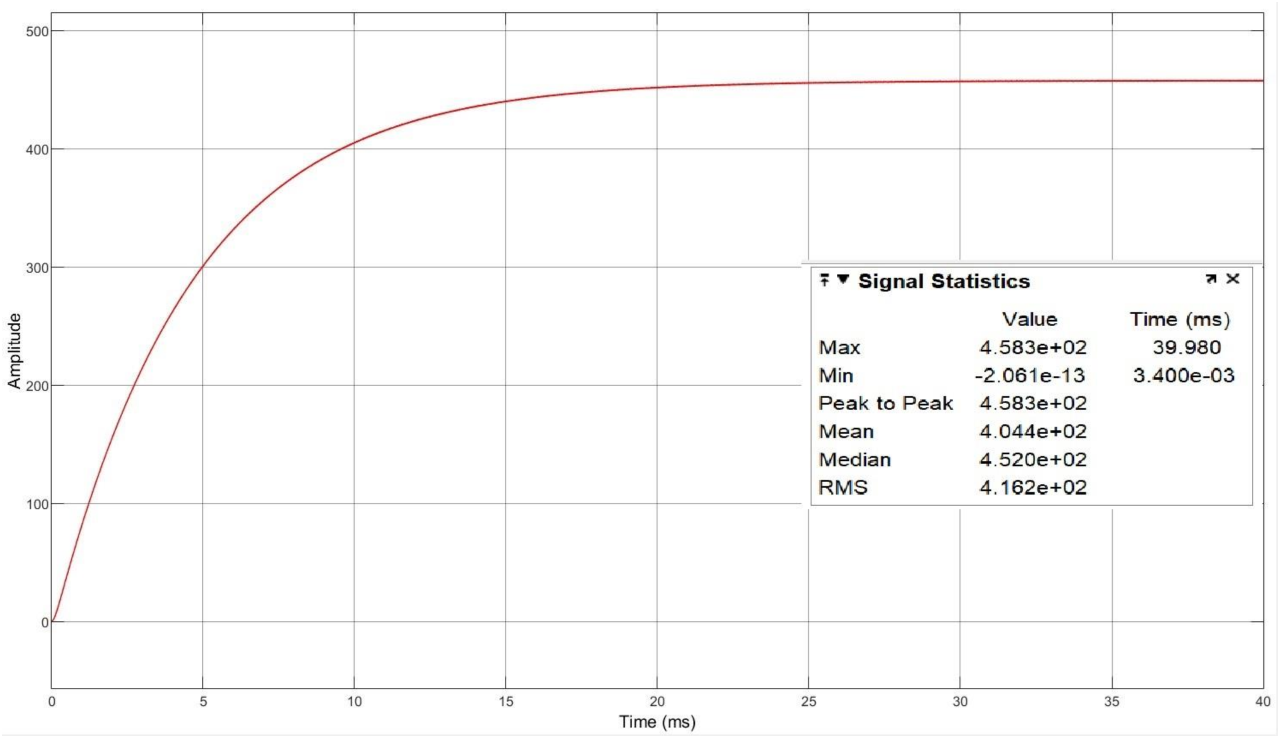


Fig. 9.c. Output Voltage (75kHz)

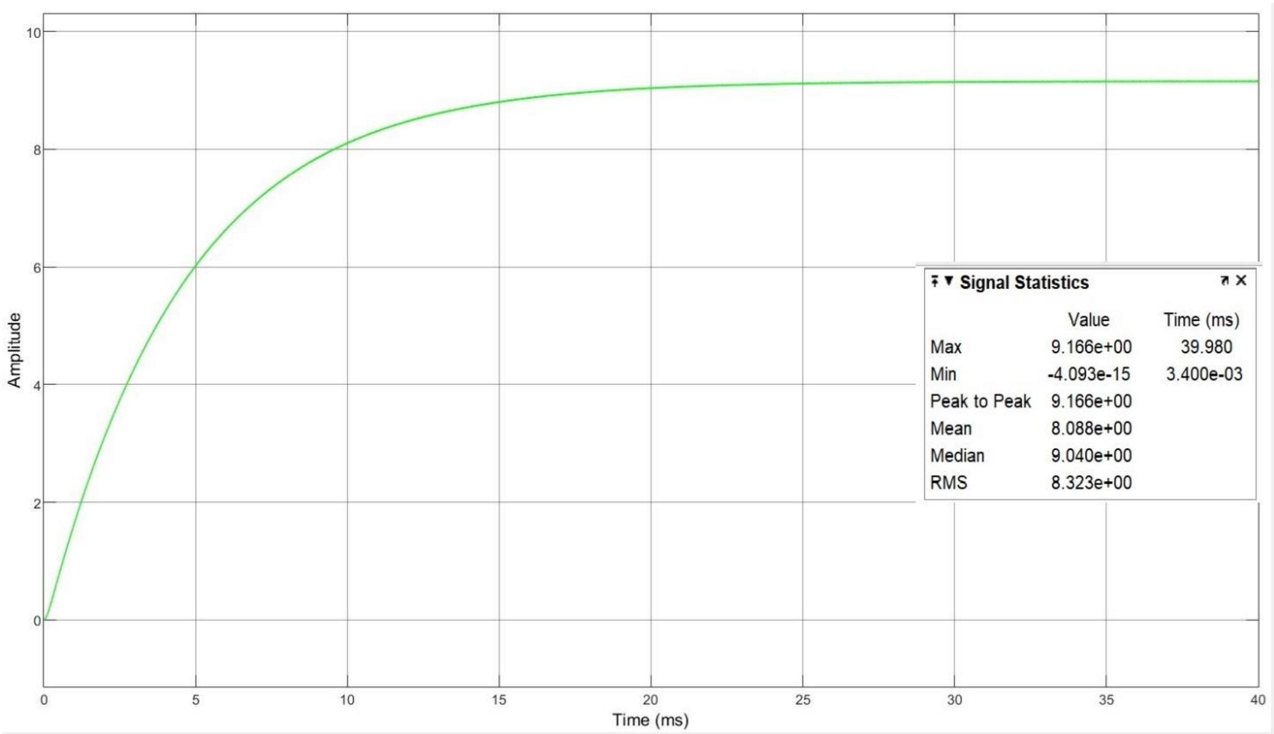


Fig. 9.d. Output Current (75kHz)

4.4.2. Table for Output Voltage, Output Power, Output Current (When Switching Frequency (f_{sw}) is 75kHz):

Δϕ (rad)	Δϕ (deg)	f (sw) (Hertz)	L (Henry)	n (Turns Ratio)	PV Vin/Vp (Volt)	Vs (Volt)	Vo (Volt)	I lk (Ampere)	Po (Watt)	Io (Ampere)
0	0	75000	0.00008	2	240.4	0	0	10.09	0	0
0.261788916	15	75000	0.00008	2	238.3	153.6	153.9	4.881	116.7255209	30.78
0.523609248	30	75000	0.00008	2	233.8	273.2	273.7	16.3	370.3245595	5.474
0.785398164	45	75000	0.00008	2	229	355.9	356.5	25.07	637.8007815	7.13
1.047187079	60	75000	0.00008	2	224.6	414.7	415.3	31.48	863.6658666	8.306
1.309007411	75	75000	0.00008	2	221.8	448	448.5	35.69	1007.440237	8.971
1.570796327	90	75000	0.00008	2	220.9	457.7	458.3	38.16	1054.567396	9.166
1.832585243	105	75000	0.00008	2	221.9	446.7	447.3	38.62	1005.19774	8.945
2.094405575	120	75000	0.00008	2	224.9	412.2	412.8	37.71	859.6134795	8.255
2.356194491	135	75000	0.00008	2	229.1	355.9	356.5	34.21	638.0792966	7.13
2.617983406	150	75000	0.00008	2	234.2	267.3	267.8	28.94	362.9615945	5.355
2.879803738	165	75000	0.00008	2	238.6	145.3	145.5	20.58	110.4934646	2.911
3.141592654	180	75000	0.00008	2	240.4	0	0	10.09	0	0

Table 7: Output Voltage, Output Power, Output Current (75kHz)

4.4.3. Graph for Output Power Vs Phase Angle (deg.) (75kHz)

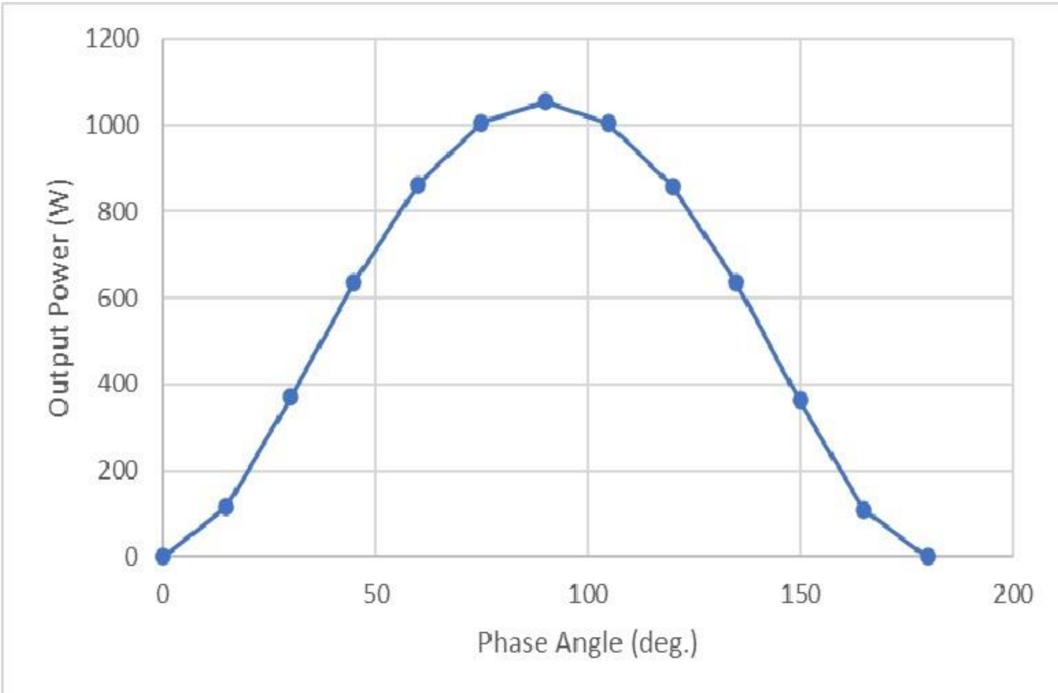


Fig. 9.e. Output Power Vs Phase Angle (deg.) (75kHz)

4.5. Comparison of Output Powers and Graphical comparison plots for different switching frequencies (30kHz, 50kHz, 75kHz)

φ (deg.)	Power (30KHz)	Power (50KHz)	Power (75KHz)
0	0	0	0
15	667.5826247	270.0587992	116.7255209
30	1785.711731	781.2104162	370.3245595
45	2589.029298	1281.747657	637.8007815
60	3020.410823	1668.697489	863.6658666
75	3213.254198	1887.226189	1007.440237
90	3269.563281	1948.75	1054.567396
105	3218.102407	1882.949768	1005.19774
120	3024.043212	1659.08726	859.6134795
135	2584.842186	1282.085859	638.0792966
150	1773.970514	752.4893837	362.9615945
165	655.1902512	207.161234	110.4934646
180	0	0	0

Table 8.: Output powers with varying Phase Angles for different switching frequencies

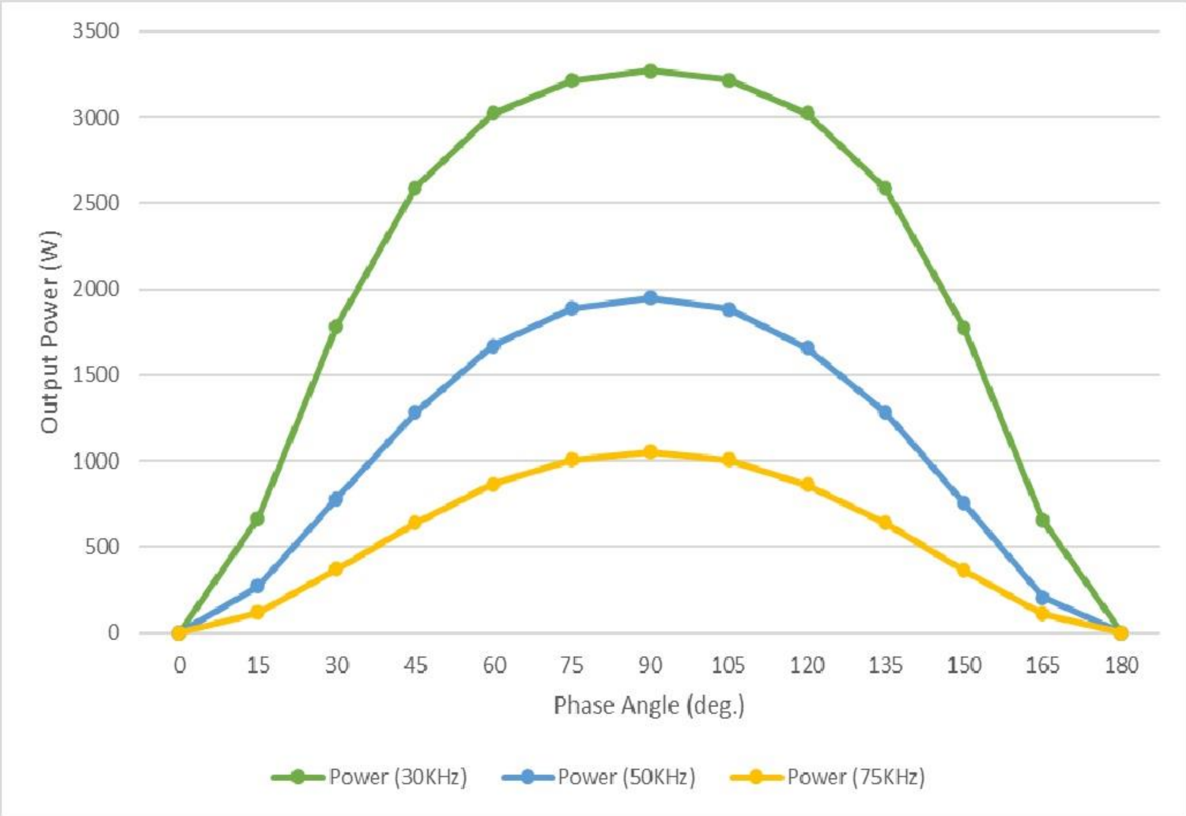


Fig. 10. Plots of Output Powers with varying Phase Angles for different Switching Frequencies

CHAPTER – V

Conclusion

Single phase-shift control of high-power DAB converters, specifically in photovoltaic applications has been studied. It involves creating a mathematical model, running MATLAB simulations, and validating the results through experimentation. It provides output power calculations with different switching frequencies and phase angles. The "SunPower SPR-295E-WHT-D" photovoltaic array has been operated at 1000W/m^2 of irradiance and 25^0 of temperature. The effectiveness of a DAB in a PV application scenario has been thoroughly examined, and data and findings have been found to show how power changes with phase angle and to determine the optimal operating point. The operating Switching Frequencies that have been used are 30kHz, 50Khz and 75kHz respectively and the Phase angle is varied from 15^0 to 180^0, considering no losses.

This study shows that the Maximum Power Transfer occurs when the Phase Angle is 90^0 for all the switching frequencies used, i.e., 30kHz, 50kHz, 75kHz, considering no losses in the DAB transformer. Also it can be demonstrated that the highest Power Transfer is offered by a Single Phase-Shifted High-Power DAB, connected to a PV Array module - “SunPower SPR-295E-WHT-D”, which is operating under a switching frequency of 30kHz at 90^0 Phase angle when the PV array has an Irradiance of 1000W/m^2 and Temp. 25^0.

Of all the three values of switching frequencies analyzed in this work, the DAB operating under 30kHz switching frequency has the highest Power Transfer, followed by the DAB operating under 50kHz switching frequency and then the DAB operating under 75kHz switching frequency.

Future Scope : The analysis done in this study can be beneficial for developing a closed-loop control of a PV system which can help maintaining the optimal operating point for achieving maximum efficiency.

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