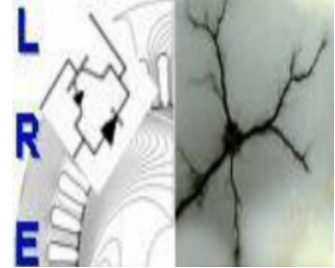


RÉPUBLIQUE ALGÉRIENNE DÉMOCRATIQUE ET POPULAIRE
MINISTÈRE DE L'ENSEIGNEMENT SUPÉRIEUR ET DE LA
RECHERCHE SCIENTIFIQUE

ÉCOLE NATIONALE POLYTECHNIQUE



المدرسة الوطنية المتعددة التقنيات
Ecole Nationale Polytechnique



Département d'Electrotechnique
Laboratoire de Recherche en Electrotechnique

Final Year Project Dissertation

To obtain the degree of State Engineer in Electrical Engineering

Modeling and Control of a PV-Powered Pumping System Using a
Switched Capacitor Inverter

BOUDOUAOU Afaf Khokha & SALMI Amel

Under the supervision of: **Dr. BENACHOUR Ali** ENSTA
Pr. MAHMOUDI Mohand-Oulhadj ENP

Presented and publicly defended on (03/07/2025)

Jury Composition

President: Pr. BERKOUK Elmadjid ENP
Supervisor: Dr. BENACHOUR Ali ENSTA
Examiner: Dr. BELKACEMI Rabie ENP

ENP 2025

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Département d'Electrotechnique

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Mémoire de projet de fin d'études

Pour l'obtention du diplôme d'ingénieur d'état en Électrotechnique

Modélisation et commande d'un système de pompage photovoltaïque
basé sur un onduleur à condensateurs commutés

BOUDOUAOUI Afaf Khokha & SALMI Amel

Sous la direction de: **Dr. BENACHOUR Ali** ENSTA
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Présenté et soutenu publiquement le (03/07/2025)

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الملخص

يتناول هذا البحث تصميم، نمذجة، ومحاكاة عاكس متعدد المستويات يعتمد على مكثفات مُبدّلة (SCMLI) مخصّص لأنظمة ضخ المياه المعتمدة على الطاقة الشمسية. يهدف العمل إلى تطوير حل فعال واقتصادي قادر على تعظيم استخراج الطاقة الشمسية مع ضمان أداء مثالي للمحرك. تم تقييم النظام تحت ظروف بيئية مختلفة باستخدام ثلاث استراتيجيات تحكم: التحكم السليبي V/f ، التحكم المباشر في العزم (DTC)، ونسخة هجينة تجمع بين DTC وتقنية التضمين الاتجاهي الفضائي (SVM). تؤكد نتائج المحاكاة قدرة العاكس على تحقيق ربح عالٍ في الجهد، تشويه توافقي منخفض، واستقرار جيد. كما تم تحليل تأثير التغيرات في درجة الحرارة والإشعاع الشمسي على أداء النظام، مما يؤكد متانته وفعالته في التطبيقات المعزولة. بالإضافة إلى ذلك، تم إجراء تحقق تجريبي لاستراتيجية التحكم V/f مما أظهر الجدوى العملية والأداء الحقيقي للنظام المقترح.

الكلمات المفتاحية: عاكس بمكثفات مُبدّلة - عاكس متعدد المستويات - نظام كهروضوئي - مضخة مياه - التضمين الاتجاهي الفضائي - استراتيجيات التحكم.

Résumé

Ce mémoire porte sur la conception, la modélisation et la simulation d'un onduleur multi-niveau à condensateurs commutés (SCMLI) destiné aux systèmes de pompage d'eau photovoltaïques. L'objectif est de développer une solution efficace et économique permettant de maximiser l'extraction de l'énergie solaire tout en assurant un bon fonctionnement du moteur. Le système est évalué sous différentes conditions environnementales à l'aide de trois stratégies de commande : le contrôle scalaire V/f , le contrôle direct du couple (DTC), et une version hybride combinant DTC et la modulation vectorielle spatiale (SVM). Les résultats de simulation valident la capacité de l'onduleur à offrir un gain de tension élevé, une faible distorsion harmonique et une bonne stabilité. L'influence des variations de température et d'irradiation solaire sur les performances du système est également analysée, confirmant sa robustesse pour les applications isolées. De plus, une validation expérimentale de la stratégie de commande V/f a été réalisée, démontrant la faisabilité pratique et les performances réelles du système proposé.

Mots clés : Onduleur à condensateurs commutés – Onduleur multiniveau – Système photovoltaïque – Pompe à eau – Modulation vectorielle spatiale – stratégies de commande.

Abstract

This thesis explores the design, modeling, and simulation of a switched capacitor multilevel inverter (SCMLI) for photovoltaic (PV) water pumping systems. The objective is to develop an efficient and cost-effective inverter capable of maximizing energy extraction from solar panels while ensuring optimal motor performance. The proposed system is evaluated under various environmental conditions and using three control strategies: scalar V/f control, Direct Torque Control (DTC), and a hybrid DTC with Space Vector Modulation (SVM). Simulation results confirm the effectiveness of the SCMLI in achieving high voltage gain, low harmonic distortion, and stable operation. The impact of temperature and solar irradiation variation on system performance is also investigated, confirming the robustness of the proposed configuration for remote and off-grid applications. Furthermore, experimental validation of the V/f control strategy was carried out, demonstrating the practical feasibility and real-world performance of the proposed system.

Keywords : Switched capacitor inverter - Multilevel inverter - PV system - water pump - Space Vector Modulation - Control strategies.

Acknowledgements

*First and foremost, we would like to express our deepest gratitude to **Dr. Ali BENACHOUR**, our supervisor, for his unwavering support, insightful guidance, and generous availability throughout this work. His expertise, constructive feedback, and encouragement played a fundamental role in the progress and completion of this thesis. We are truly grateful for his involvement at every step.*

*We also extend our sincere thanks to **Pr. MAHMOUDI**, our co-supervisor, for his valuable input, technical guidance, and support throughout this project. His contribution has been instrumental in the successful development of our work, and we are truly thankful for his involvement.*

*We would also like to deeply thank **Mrs. Rania OMAR-AMRANI** for her constant support, kindness, and patience. Her help, whether technical or moral, has meant a great deal to us, and her encouragement never went unnoticed.*

*Our sincere thanks go to **Pr. BERKOUK**, for accepting to chair our thesis jury. His presence is a true honor for us.*

*We also thank **Dr. BELKACEMI** for kindly agreeing to evaluate our work and for the time and attention he has devoted to it.*

We would like to warmly thank all the professors who accompanied us throughout these three years of the second cycle. Their teaching, guidance, and dedication have been essential in shaping our knowledge and mindset.

Lastly, we express our sincere gratitude to all those who have contributed in one way or another to the successful completion of this thesis. Your support, guidance, and encouragement have been invaluable, and we are deeply thankful for your presence throughout our academic journey.

To all those who supported us, challenged us, or inspired us — thank you.

Afaf & Amel

Dedication

To my beloved parents, With deepest love and gratitude.

To my late father, whose memory continues to guide and inspire me every day — your recent departure has left an indescribable void, one that words can hardly fill. yet your presence lives on in every choice I make and every value I uphold. You were my quiet strength, my role model, the foundation of my determination and my greatest source of inspiration. Every step I've taken in this journey carries a part of you. This work is dedicated to your memory — a small way of honoring all that you've given me. I carry your love with me, always.

To my mother, whose endless support and sacrifices have shaped the person I am today — thank you for your unwavering faith in me.

And to my wonderful sisters Lina, Mounia, Louisa — thank you for your constant encouragement, your laughter, your support and the unique bond of understanding and love that unites us. Your presence in my life brings light and motivation. I am forever grateful to have you by my side, and I cherish each and every one of you deeply.

And to all the incredible friends I've met during my time at Polytech — thank you for the memories, the shared struggles, and the laughter. Your companionship has made this journey richer, brighter, and truly unforgettable.

To all the new acquaintances I've had the pleasure of meeting throughout this PFE journey — thank you for the insightful exchanges, the shared moments, and the fresh perspectives. Each encounter, no matter how brief, has enriched this experience in its own unique way.

My special thanks to Afaf, my project partner, for her dedication and commitment throughout this project, which I truly acknowledge and appreciate.

Amel

Dédicaces

À maman, l'incroyable femme que tu es, celle qui sait aimer sans limites, et papa, piliers de ma vie, pour leur amour sans faille, leurs sacrifices et leur foi constante en moi. J'espère un jour être à la hauteur de tout ce que vous m'avez donné.

À Aymen et Fifi, pour leur affection, leur soutien parfois bruyant mais toujours sincère, et tous ces petits moments partagés qui comptent plus qu'ils n'en ont l'air. Merci d'être mon équipe à vie.

À mes incroyables tantes, Khalto Amel et Nana, pour leur présence constante et leur amour inconditionnel.

À Djawed, le rayon de soleil de notre famille, merci pour la joie que tu nous apportes chaque jour. Je t'aime très fort.

À mes amis, Manel, Benz et Bousri, les soleils de ma vie, et mes sœurs, ainsi que Raouf, Mouad et Malik, pour tous les moments inoubliables partagés et les fous rires jusqu'aux larmes. Merci pour votre amitié immuable et d'être cette seconde famille que la vie m'a offerte.

À Meryem, pour les pauses café, les fous rires, le soutien moral... et surtout ta présence rassurante.

À mes magnifiques rencontres : Kassia, Meriem, Hadjer, Soundous, Leyla et Rania, merci d'avoir partagé ce bout de chemin avec moi. Ce fut un plaisir.

À Sarah, ma précieuse découverte de l'année, pour sa présence, son écoute et ses encouragements constants, malgré les kilomètres. Merci d'avoir été là.

À toutes celles et ceux dont nos chemins se sont croisés un jour.

À Amel, mon binôme, pour sa disponibilité et son engagement tout au long de ce projet, que je reconnais et apprécie.

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List of acronyms

- **AC** : Alternating Current
- **DC** : Direct Current
- **DTC** : Direct Torque Control
- **EMI** : Electromagnetic Interference
- **FFT** : Fast Fourier Transform
- **IGBT** : Insulated Gate Bipolar Transistor
- **IM** : Induction Motor
- **IV Curve** : Current-Voltage Curve
- **MLI** : Multilevel Inverter
- **MPPT** : Maximum Power Point Tracking
- **NPSH** : Net Positive Suction Head
- **PI** : Proportional-Integral (Controller)
- **PV** : Photovoltaic
- **PWM** : Pulse Width Modulation
- **SCI** : Switched Capacitor Inverter
- **SCMLI** : Switched Capacitor Multilevel Inverter
- **SPVWPS** : Solar Photovoltaic Water Pumping System
- **SVM** : Space Vector Modulation
- **TDH** : Total Dynamic Head
- **THD** : Total Harmonic Distortion
- **V/f** : Voltage over Frequency
- **VSI** : Voltage Source Inverter

General introduction

Solar-powered water pumping systems have emerged as a promising and sustainable solution for meeting water needs in isolated and off-grid regions. By harnessing the abundance of solar energy, these systems provide a clean alternative to conventional pumping methods that rely heavily on grid electricity or fuel-based generators. Their autonomy and environmental friendliness make them particularly attractive in rural and agricultural settings.[1]

At the heart of these systems lies the **inverter**, a key component that transforms the **direct current (DC)** produced by photovoltaic (PV) panels into **alternating current (AC)** required to drive electric pumps. The performance and efficiency of the inverter directly influence the overall effectiveness of the pumping system.[2]

In traditional PV-driven motor drive systems, a two-stage power conversion is commonly used. This includes a **DC-DC boost converter** to raise the voltage from the PV panels, followed by a **DC-AC inverter** to power the motor. While effective, this configuration increases system complexity, cost, and size due to the presence of inductive components (coils or transformers), especially at higher voltage levels.[3] Moreover, the switching losses and reduced efficiency under varying solar conditions make such systems less optimal for low-cost standalone applications.[4]

To overcome these limitations, researchers have explored the use of **switched capacitor multilevel inverters (SCMLIs)**. These topologies integrate voltage boosting and inversion in a single stage, eliminating the need for magnetic components. They also generate **multiple output voltage levels**, which helps reduce **total harmonic distortion (THD)** and improve power quality.[5][6] Such characteristics make SCMLIs particularly well-suited for PV applications, where compactness, cost-efficiency, and high voltage gain are crucial.

To further optimize the performance of SCMLIs in solar pumping systems, the choice of modulation and control strategy is essential. In this context, **Space Vector Modulation (SVM)** has proven to be an effective technique for improving output waveform quality and reducing harmonic content.[7] Additionally, different control approaches — including **scalar V/f control**, **Direct Torque Control (DTC)**, and a hybrid method combining **DTC with SVM** — allow for a comparative evaluation of system dynamics and energy efficiency.[8]

In this thesis, we aim to study, model, and implement a **switched capacitor inverter topology adapted for PV-powered water pumping systems**. Through simulations under various environmental conditions and control strategies, we assess the inverter's performance in terms of **voltage gain**, **power delivery**, and **motor control**. The impact of **irradiation and temperature variations** on system behavior is also analyzed to ensure reliability in real-world applications. In addition to simulation studies, an **experimental setup is developed** to validate the practical implementation of the proposed system. The key functionalities

of the inverter **are tested**, demonstrating its ability to drive an **induction motor coupled to a pump load** using PV power under **basic V/f control**, supporting the feasibility and relevance of the proposed topology for **real-world deployment** in standalone solar pumping applications.[9]

By integrating advanced inverter design with efficient control methods, this research contributes to the development of **high-performance and accessible solar pumping solutions**, supporting the broader goal of energy sustainability and water security in underserved areas.[9]

Chapter 1

Review of switched capacitor inverters and PV systems

Introduction

In recent years, the rapid depletion of fossil fuel reserves and growing environmental concerns have accelerated the global shift toward renewable energy sources. Among these, solar energy has emerged as a leading alternative due to its abundance, cleanliness, and accessibility.[10] [11] Photovoltaic (PV) systems, which directly convert sunlight into electricity, have gained significant attention for their sustainability and diverse applications. One of the most promising uses of PV technology is in water pumping systems, particularly in remote or off-grid areas where access to electrical infrastructure is limited.[12] [9]

Despite their advantages, PV systems face efficiency challenges due to variability in solar irradiation, temperature, and load conditions. These factors significantly affect the overall energy conversion and system performance.[14] A crucial stage in the PV system is the DC-AC conversion process, which enables the transformation of the PV-generated direct current (DC) into alternating current (AC) to power loads such as electric motors. Multilevel inverters (MLIs) have become a widely adopted solution for this purpose, especially in medium- and high-power applications, due to their ability to synthesize high-quality output voltages, reduce total harmonic distortion (THD), and minimize the need for large output filters.[15]

Traditional MLI topologies—such as cascaded H-bridge (CHB), neutral point clamped (NPC), and flying capacitor (FC) inverters—often require front-end boost converters or impedance networks to raise the input voltage to the desired levels.[16] However, these additional stages increase system complexity, size, cost, and introduce further power losses. To address these limitations, switched-capacitor multilevel inverters (SCMLIs) have been proposed as a compact and efficient alternative. These topologies utilize cascaded switched-capacitor cells capable of self-voltage boosting, eliminating the need for inductive components and conventional boost converters.[17][18]

This chapter explores the evolution of multilevel inverter topologies, with a focus on the advantages offered by switched-capacitor structures compared to conventional designs. Furthermore, a general overview of PV systems and their role in driving water pumping solutions will be presented, emphasizing the sustainability and cost-effectiveness of such configurations in real-world rural applications.[19]

1.1 Review of switched capacitor inverters

1.1.1 Voltage Boosting Techniques

Boosting the low DC voltage generated by solar panels to the required levels is essential for efficient energy conversion. This is typically done using high step-up DC-DC converters or transformers integrated with inverters. Various techniques enhance voltage gain and efficiency by employing energy storage components like capacitors and inductors, as well as semiconductor switches and diodes. Some of the most effective methods include switched capacitor, switched inductor, voltage lift, magnetic coupling, and voltage-multiplying cells. These approaches provide higher voltage gains than conventional boost converters while addressing their limitations. [20]

1. **Switched Capacitor :** The switched capacitor (SC) technique boosts voltage using a charge pump (CP), which transfers energy between capacitors through controlled switching. With each cycle, the output voltage increases. Unlike magnetic-based converters, SC circuits use only capacitive storage, making them compact and immune to electromagnetic interference. Their modular, scalable design supports monolithic integration and makes them efficient for various applications, including integrated circuits and power electronics. [21]

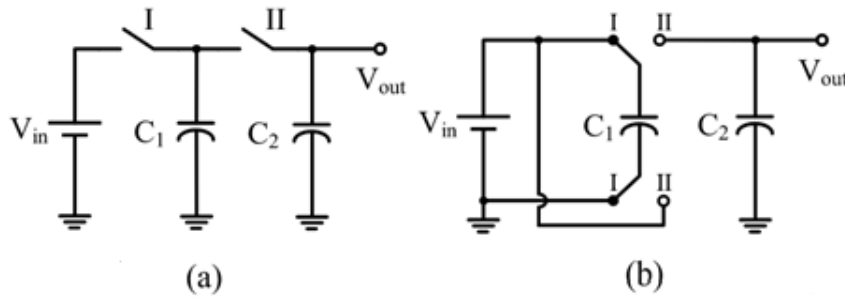


Figure 1.1: (a) Basic charge pump (b) basic switched capacitor
[21]

2. Magnetic Coupling :

Magnetic coupling is commonly used for voltage boosting in both isolated and non-isolated DC-DC converters. Transformer-based methods offer high voltage gain and electrical isolation by adjusting the transformer's turns ratio. While line-frequency transformers suit high-power applications, they are bulky and expensive due to large magnetic cores. Coupled inductors help reduce core size and improve layout efficiency. However, magnetic coupling introduces leakage inductance, which can cause energy losses, often requiring auxiliary circuits to recover the lost energy and enhance efficiency. [21]

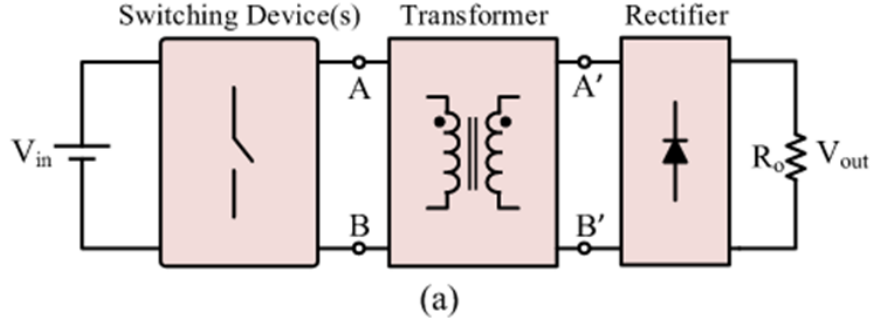


Figure 1.2: Magnetic Coupling
[21]

3. Multistage :

The multistage (or multilevel) technique boosts voltage by cascading converter modules that use capacitors, diodes, and switches to generate higher output levels. Common in renewable systems like PV, batteries, or fuel cells, this method enables high-voltage AC outputs from distributed DC sources. It offers modularity, ease of maintenance, and high power density, as more cells can be added without large transformers. However, it increases system cost, complexity, and size due to the greater number of components.[21]

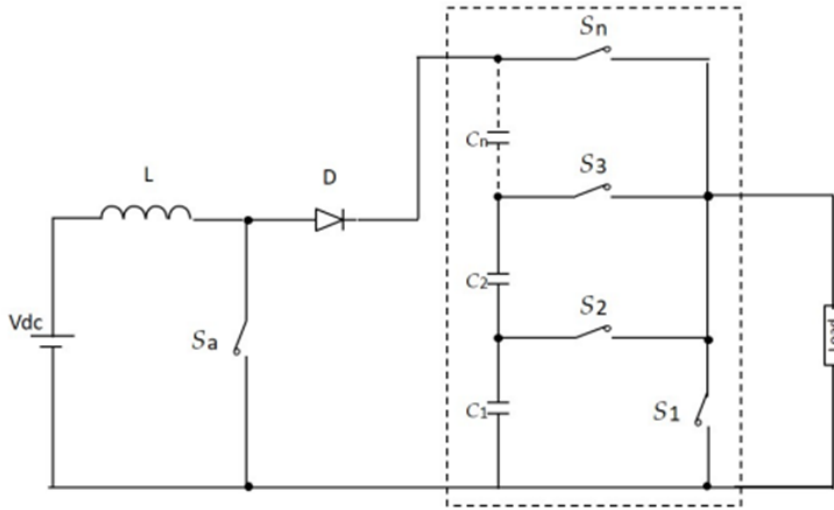


Figure 1.3: DC/DC multi-level boost converter
[21]

SC circuits are compact, cost-effective, and free from bulky magnetic components, making them highly suitable for PV systems, especially in low-to-medium power applications. Their modularity and simplicity make them advantageous over the bulkier magnetic coupling and more complex multistage systems.

1.1.2 Advantages of switched capacitor inverters

Switched-capacitor (SC) inverters are increasingly favored in applications requiring compact, efficient, and reliable power conversion. Their design offers several advantages that make them suitable for modern high-performance systems: [22]

- Low total harmonic distortion (THD) and high-quality output.
- Minimal electromagnetic interference (EMI).
- Fewer semiconductor devices needed, with manageable voltage stress on switches.
- Higher output voltage gain using single or multiple DC sources.
- Reduced current stress and losses via soft charging or PWM techniques.

These features contribute to improved power density and efficiency, making SC inverters a strong choice for advanced power systems.[22]

1.1.3 Review of Three Phase Switched Capacitor Inverters Topologies

1.1.3.1 First Topology :Three-Phase Boost Multilevel Inverter Based on Coupled-Structure Switched-Capacitor and V^2 SVM

Description : The first topology is a three-phase SCMLI with a boost factor of 3 and seven line-to-line voltage levels. It uses a triple-mode SC unit consisting of an H-bridge, two diodes, and two capacitors to feed a three-phase inverting bridge. Two optional DC-link capacitors split the DC input voltage but are unnecessary for three-phase three-wire applications. The front-side H-bridge enables different capacitor configurations, ensuring self-balanced voltages and generating voltage levels of $2E$, $4E$, or $6E$ to supply the inverting bridge through diodes. [23]

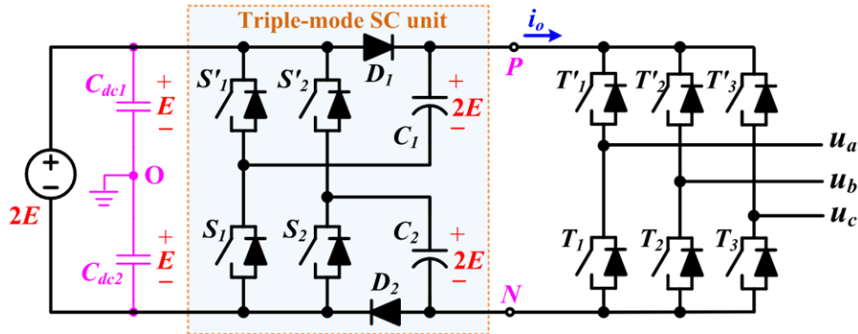


Figure 1.4: Three-Phase Boost Multilevel Inverter Based on Coupled-Structure Switched-Capacitor

[23]

Modulation Technique : The Three-Phase SCMLI employs an improved Vector 2 Space Vector Modulation (V^2 SVM) technique to enhance precision and reduce harmonics. It forms a virtual vector (V_s) by averaging two adjacent medium vectors, dividing each sector into smaller triangles. The reference vector (V_{ref}) is synthesized using the nearest triangle vectors, minimizing switching stress and harmonics. A seven-step switching sequence, limiting voltage changes to $2E$, ensures symmetry and high output quality. [23]

Advantages : This SCMLI topology achieves a voltage boost factor of 3 and generates 7 line-to-line voltage levels, significantly lowering THD. With 97.6% efficiency, a compact structure, and fewer components, it reduces switching stress and EMI. Advanced modulation minimizes voltage ripple, ensuring stable operation under dynamic loads. [23]

Disadvantages : The system requires complex V²SVM modulation for precise control and experiences high voltage stress, with components facing up to three times the input voltage. It also demands careful parameter tuning for optimal performance and has limited scalability, making it primarily suitable for low-voltage applications. Furthermore, ripple sensitivity increases under high load conditions, which can impact stability. [23]

1.1.3.2 Second Topology :An optimized leg integrated switched capacitor inverter (LISCI) topology for 3- induction motor

Description : The Leg-Integrated SC Inverter (LISCI) is a compact, single-stage SC boost inverter that reduces size, weight, and total voltage stress (TVS) by integrating the SC unit into phase A. It generates a quasi three-level output using 8 switches, 2 diodes, and 2 SCs. The unique phase-A structure enables both three-level voltage generation and SC charging, eliminating extra components found in traditional inverters. [24]

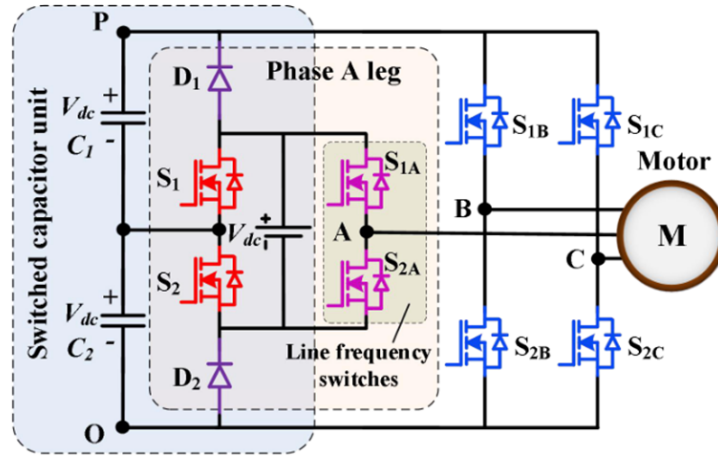


Figure 1.5: An optimized leg integrated switched capacitor inverter (LISCI) topology [24]

Modulation Technique : The modulation technique for this topology involves a novel Pulse Width Modulation (PWM) strategy tailored for its unique space vector hexagon with 12 vectors. Phase A generates a 3-level pole voltage, requiring two level-shifted triangular carriers (c_{S2} and c_{S3}) for modulation, while phases B and C produce 2-level pole voltages using a single triangular carrier (c_{S1}). [24]

Advantages: The LISCI inverter achieves voltage boosting without bulky inductors, reducing component count, cost, and complexity. Its compact design integrates the SC within the inverter leg, enhancing space efficiency. High efficiency is ensured through lower switching losses and reduced harmonic distortion (THD). The system maintains self-balancing SC voltages without extra control and allows scalability for higher voltage or multilevel applications. Additionally, it supports regenerative braking for energy recovery. [24]

Disadvantages: The inverter relies heavily on large, high-value SCs, and its asymmetric operation results in unequal pole voltage levels across phases. Implementing complex PWM strategies is necessary, and the design is primarily suited for low-power applications. Voltage ripple increases at higher power levels, potentially affecting stability, while uneven dv/dt stress across phases impacts EMC and insulation reliability. [24]

1.1.3.3 Third Topology :Generalized Structure for Three Phase Switched Capacitor Boost Inverter with Adapted Space Vector Modulations

The third topology combines a three-phase voltage source inverter with three cascaded switched capacitor (SC) converters. Each SC stage connects to the input voltage V_{DC} via a diode D_i and consists of a capacitor C_i and two complementary switches (S_i and S'_i), which can be IGBTs or power MOSFETs. This complementary switching prevents short-circuiting the voltage source. The SC stages are cascaded by linking the capacitor of one stage to the switch of the next. [25]

During operation, the capacitors charge to V_{DC} when connected in parallel to the input via the diodes and discharge when connected in series with it. This configuration allows the input voltage to be boosted up to $4V_{DC}$. [25]

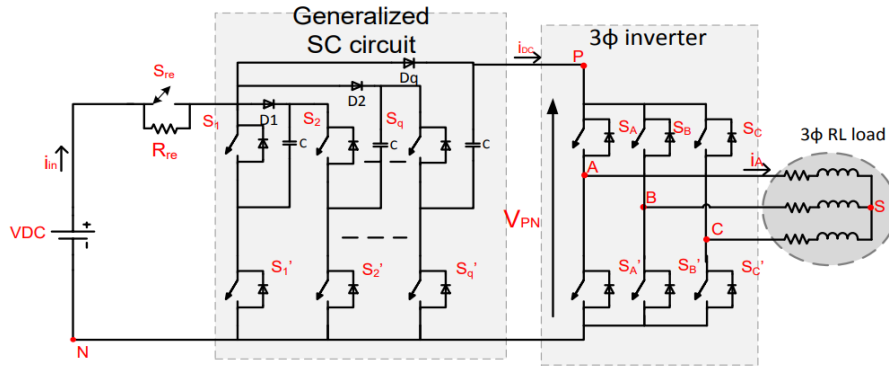


Figure 1.6: Generalized Structure for Three Phase Switched Capacitor Boost Inverter [25]

Advantages: The proposed switched-capacitor boost inverter eliminates the need for a separate DC-DC converter, extending the voltage range while reducing size, weight, and power losses. Its multilevel output enhances waveform quality and lowers harmonic distortion, improving efficiency, especially in renewable energy applications. Additionally, the adapted space vector modulation techniques optimize performance, with SVM3 offering the best efficiency. [25]

Disadvantages: The inverter requires a more complex control system with advanced gate drivers and modulation strategies. The increased number of switches and capacitors raises costs and design complexity, while inrush currents may require additional protective circuits. Some components experience higher voltage stress, demanding more robust parts. At higher power levels, efficiency declines due to capacitor charging constraints. [25]

1.1.3.4 Comparative Study

A comparison is conducted with respect to different parameters in Table 1.1 of the different single-phase capacitor switched capacitor inverter structures.

- N_{dc} : Nombre de sources de tension continue.
- N_{sw} : Nombre d'interrupteurs.
- N_{gd} : Nombre de pilotes de grille.

- N_D : Nombre de diodes.
- N_C : Nombre de condensateurs.
- N_L : Nombre d'inductances.
- N_{level} : Nombre de niveaux de sortie.
- G_m : Gain maximal.
- TSV : Tension totale supportée.
- MVS : Contrainte de tension maximale.

Below is the proposed performance index formula allowing us to compare these three structures :

$$\text{Performance index} = 0.6 \cdot \frac{\text{gain}}{N_{\text{switches}}} + 0.2 \cdot \frac{\text{gain}}{N_{\text{capacitors}}} + 0.15 \cdot \frac{N_{\text{levels}}}{N_{\text{switches}}} + 0.05 \cdot \frac{N_{\text{levels}}}{N_{\text{capacitors}}}$$

Topology	N_{dc}	N_{sw}	N_{gd}	N_D	N_C	N_L	N_{level}	G_m	TSV	MVS	N_{sw}/N_{level}	Efficiency	Performance index
1	1	10	5	2	2	0	7	3	/	/	1.42	97.8%	0.76
2	1	8	/	2	2	0	7	2	$14V_{dc}$	$0.5V_{dc}$	1.14	95.79%	0.66
3	1	12	/	3	3	0	9	4	/	$4V_{dc}$	3	96%	0.73

Table 1.1: Comparison of Different Topologies

Based on the results of the comparative study table, it can be concluded that:

- Topology 1 has the highest performance index (0.76) and achieves 97.8% efficiency, producing 7 voltage levels with a gain of 3. It balances efficiency and complexity with moderate component count (10 switches, 2 diodes, 2 capacitors) but requires complex V^2SVM modulation and faces high voltage stress ($3 \times V_{dc}$). Best suited for low-voltage applications requiring high efficiency and output quality.
- Topology 2 has the lowest performance index (0.66) with 95.79% efficiency and a voltage gain of 2. It benefits from self-balancing SC voltages and a compact design, but voltage ripple issues and asymmetric pole voltages limit scalability. Works well for low-power applications like motor drives if ripple is managed.
- Topology 3 achieves a performance index of 0.73, offering the highest voltage gain (4) with 96% efficiency. It eliminates the need for a separate DC-DC converter, improving waveform quality, but requires more components (12 switches, 3 diodes, 3 capacitors) and complex modulation. Efficiency declines at higher power levels due to capacitor charging constraints, making it ideal for renewable energy applications requiring high voltage gain.

Each topology presents trade-offs, and selection depends on efficiency, voltage gain, and control complexity, with Topology 1 leading in overall performance.

1.1.4 Challenges and Limitations of Switched Capacitor Inverters

While SC-MLIs offer advantages such as voltage boosting and self-voltage balancing, they face significant challenges that hinder their performance and applicability in certain scenarios:[22]

- **Pulsating Current Stress:** Capacitor charging generates large current surges, increasing switch stress and reducing efficiency.
- **Capacitor Voltage Ripple:** Voltage fluctuations across capacitors can distort output and stress components, especially in high-power applications.
- **High Electromagnetic Interference (EMI):** Inductorless operation leads to EMI, impacting system reliability and compatibility.
- **Soft Start and Inrush Current Issues:** Uncharged capacitors at start-up cause large inrush currents, potentially damaging components and requiring soft-start circuitry.
- **Complex Modulation and Control:** Advanced modulation techniques increase control complexity, making implementation more challenging.
- **Thermal Management Challenges:** High current stress and switching losses cause heat buildup, requiring effective cooling solutions.
- **Limited Fault-Tolerance:** Many SC-MLI designs lack redundancy, making them prone to failures and increasing maintenance costs.

1.1.5 Key solutions for SCIs limitations

To overcome the challenges faced by switched-capacitor inverters, several innovative solutions have been proposed. These strategies focus on improving efficiency, reducing component stress, and enhancing system reliability, making these inverters more viable for a wide range of applications: [22]

- **PV Source Integration:** PV sources inherently limit current during startup, thereby helping to suppress inrush currents and protect circuit components.
- **Hybrid Modulation Techniques:** Combining level-shifted and phase-shifted PWM to optimize capacitor charging/discharging and reduce ripple.
- **Quasi-Soft Charging (QSC) Operation:** Adding small inductors to limit pulsating currents, reducing stress on switches and EMI.
- **Soft-Start Techniques:** Using relays and resistors to gradually charge capacitors, preventing inrush currents and protecting components.
- **Hybrid Topologies:** Integrating SC-MLIs with flying capacitors or switched-boost circuits to enhance voltage gain and fault tolerance.
- **Generalized and Modular Designs:** Developing scalable SC-MLI structures for higher voltages and adaptable applications.
- **Improved Thermal Management:** Implementing advanced cooling strategies to handle heat from high current stress and switching losses.
- **Fault-Tolerant Designs:** Using redundant switches or capacitors to maintain operation despite component failures.

1.1.6 Applications of Switched-Capacitor inverters

Switched-capacitor converters (SCCs) have emerged as a promising technology in power electronics, offering unique advantages such as voltage boosting, compact design, and self-voltage balancing. These features enable their use in a variety of cutting-edge applications across multiple industries: [22]

- **Renewable Energy Systems:** Used in photovoltaic (PV) inverters for grid-tied applications, providing voltage boosting and transformerless operation to reduce size and cost.
- **High-Frequency Power Distribution:** Applied in microgrids and electric aircraft due to their compact design and ability to operate at high frequencies.
- **Electric Vehicles (EVs):** Used for battery balancing and power conversion in EVs, enhancing energy management and efficiency.
- **Industrial Motor Drives:** Employed in motor drives to generate high-quality multilevel output voltages, improving motor control and efficiency.
- **High-Voltage Pulse Generators:** Inspired by Marx converter principles, SC-MLIs are used in applications like plasma generation, sterilization, and water treatment.

1.2 Review of PV systems

1.2.1 PV cells

1.2.1.1 Definition and Operating Principle

A photovoltaic (PV) cell, or solar cell, is a semiconductor device—typically made of silicon—that directly converts sunlight into electricity via the photovoltaic effect. When photons from sunlight hit the cell, they energize electrons, freeing them from atoms. An internal electric field, formed by doping, directs these electrons to generate a direct current (DC). This clean and efficient process requires no moving parts. [26]

1.2.1.2 Types of PV Cells

1. **Silicon-Based PV Cells** are the most widely used, made from silicon, a durable and efficient semiconductor. [27]

- ✓ **Monocrystalline Silicon**

- Single-crystal structure.
- High efficiency (15–22%), suitable for space-limited installations.
- Long lifespan (over 25 years), but higher cost.

- ✓ **Polycrystalline Silicon**

- Made from multiple silicon crystals.
- Lower efficiency (13–16%) but more affordable.

2. **Thin-Film PV Cells** are made by layering PV material on glass or plastic. They're lightweight, flexible, and cheaper to produce, but less efficient. (EIA) 2023

✓ **Cadmium Telluride (CdTe)**

- Cost-effective and good for large-scale systems.
- Performs well in real-world conditions despite lower efficiency.

✓ **Copper Indium Gallium Diselenide (CIGS)**

- High lab efficiency, flexible, and ideal for curved surfaces.
- Manufacturing is complex due to its multi-element composition.

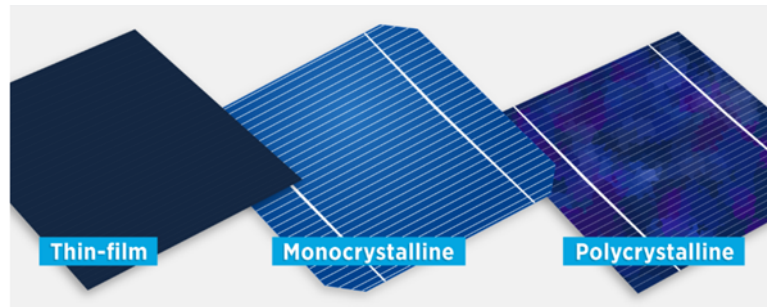


Figure 1.7: Silicon-based and thin-film PV cells
[28]

3. **Organic PV Cells (OPV)** are made from carbon-based materials. They're flexible and lightweight but still under development and not widely commercialized.

- Flexible and semi-transparent.
- Lower efficiency (10%) and shorter lifespan.
- Suited for portable and building-integrated applications (BIPV).

4. **Perovskite PV Cells** are gaining attention for their low production costs and fast efficiency improvements.

- Lab efficiency exceeds 25%.
- Simple to manufacture.
- Challenges include limited durability and large-scale production.

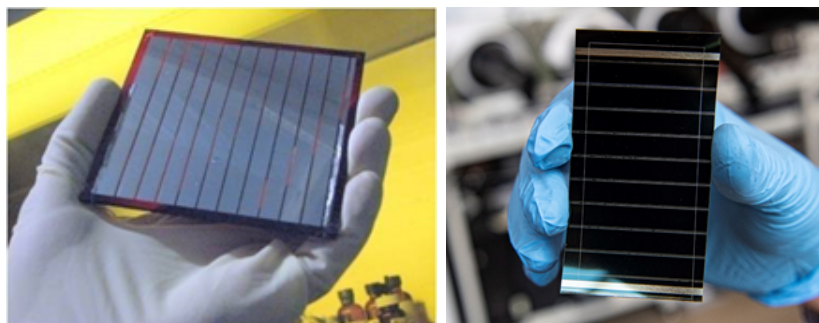


Figure 1.8: Organic PV cells, Perovskite PV cells
[29] [30]

5. Other Types

✓ Quantum Dot Solar Cells

- Use nanoscale semiconductors.
- Tunable light absorption, ideal for flexible and small-scale devices.
- Still in early-stage research.

✓ Multijunction PV Cells

- Layered materials absorb different light wavelengths.
- Very high efficiency (40%+), mostly used in aerospace.
- Expensive and complex to produce.

✓ Concentration PV (CPV)

- Use lenses/mirrors to focus sunlight on high-efficiency cells.
- Efficient and material-saving.
- Require tracking systems; suited for large sunny regions.

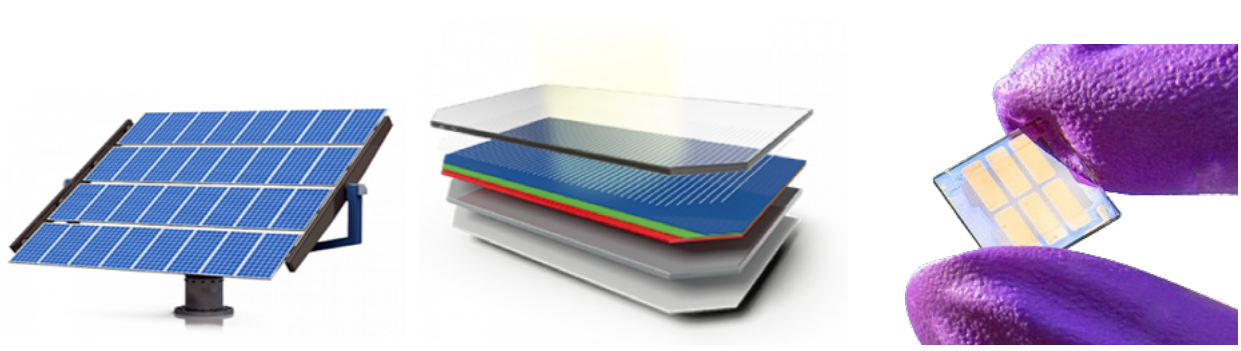


Figure 1.9: Concentration PV cells, Multijunction PV cells, Quantum Dot Solar Cells
[31][32][33]

1.2.1.3 PV cells modeling and characteristics

1. PV cell modeling

There are several models of photovoltaic cells that differ in their mathematical procedures and the number of parameters involved in the calculation of current and voltage. In this study, we consider a five-parameter model represented by an electrical circuit. This circuit consists of an ideal current source that characterizes the photocurrent (proportional to the light intensity), a diode representing the semiconductor properties of the cell, a series resistance that accounts for Joule losses, and a shunt resistance characterizing the leakage current. If the two resistances are neglected, the electrical circuit of the cell is considered ideal. [34] [35]

The equivalent circuit of the photovoltaic cell studied is shown in the following figure:

Development of the Mathematical Model

Using Kirchhoff's law (node law) on the circuit of a real cell, the following equation is obtained:

$$I_{PV} = I_{ph} - I_D - I_{sh} \quad (\text{II.1})$$

Where:

- I_{PV} : is the output current from the cell.
- I_{ph} : is the photocurrent.

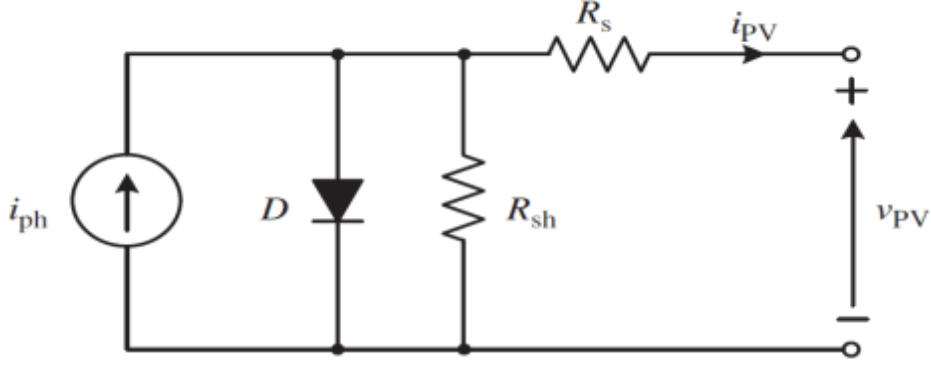


Figure 1.10: Equivalent circuit of a PV cell

- I_D : is the current passing through the diode.
- I_{sh} : is the current passing through the shunt resistance.

The diode current I_D can be defined as:

$$I_D = I_s \left(e^{\frac{V_D}{V_{th}}} - 1 \right) \quad (\text{II.2})$$

Where:

$$V_D = V_{PV} + R_s I_{PV}$$

Thus, the expression of I_D becomes:

$$I_D = I_s \left(e^{\frac{V_{PV} + R_s I_{PV}}{V_{th}}} - 1 \right) \quad (\text{II.3})$$

Where:

- I_s : Reverse saturation current of the diode.
- V_{th} : Thermal voltage defined as $V_{th} = \frac{nkT}{q}$.
- n : Ideality factor of the P-N junction.
- k : Boltzmann constant ($k = 1.3806503 \times 10^{-23}$ J/K).
- T : Operating temperature of the cell.
- q : Electron charge ($q = 1.602 \times 10^{-19}$ C).

The shunt current I_{sh} is given by:

$$I_{sh} = \frac{V_{PV}}{R_{sh}} = \frac{V_{PV} + R_s I_{PV}}{R_{sh}} \quad (\text{II.4})$$

Substituting equations (II.3) and (II.4) into equation (II.1), the cell model is derived as:

$$I_{PV} = I_{ph} - I_s \left(e^{\frac{V_{PV} + R_s I_{PV}}{V_{th}}} - 1 \right) - \frac{V_{PV} + R_s I_{PV}}{R_{sh}} \quad (\text{II.5})$$

The expressions for I_{ph} and I_s are given as:

$$I_{ph} = \frac{G}{G_o} [I_{sc} + k_i(T - T_o)] \quad (\text{II.6})$$

$$I_s = I_{s0} \left(\frac{T}{T_o} \right)^3 e^{\frac{qE_g}{nk} \left(\frac{1}{T_o} - \frac{1}{T} \right)} \quad (\text{II.7})$$

Where:

- I_{sc} : Short-circuit current under standard conditions.
- G : Solar irradiation.
- G_o : Nominal solar illumination.
- k_i : Temperature coefficient of I_{ph} .
- T_o : Nominal temperature.
- E_g : Bandgap energy of silicon.
- I_{s0} : Diode saturation current under standard conditions.

2. PV cell characteristics

A PV cell is defined by the following key parameters:

- **Short-Circuit Current (I_{sc}):** The short-circuit current is the current generated by a photovoltaic (PV) cell when the voltage across its terminals is zero, meaning the terminals are shorted. It represents the maximum current the PV cell can produce under standard test conditions. This value is crucial because it indicates the upper limit of the current that the cell can deliver when connected to a circuit.
- **Open-Circuit Voltage (V_{oc}):** The open-circuit voltage refers to the voltage across the PV cell when there is no current flowing, as the terminals are open. It represents the maximum voltage the PV cell can produce under standard illumination and temperature conditions. This parameter provides an essential measure of the potential energy output of the PV cell.
- **Maximum Power Point (MPP) :** The maximum power point (MPP) is the point on the I-V curve where the PV cell generates its maximum power. At this specific point, the product of the voltage (V) and current (I) reaches its peak value, expressed as:

$$P_{\max} = V_{\text{MPP}} \times I_{\text{MPP}} \quad (1.1)$$

This is the most critical operating point for practical applications, as it determines the maximum power output achievable by the PV system.

- **I-V and P-V Curves :** To fully understand the behavior of a PV cell, it is essential to examine its I-V curve and P-V curve:
 - The **I-V curve** demonstrates how the current varies with voltage.
 - The **P-V curve** highlights the power output at different voltage levels.

Together, these curves serve as critical tools for evaluating and optimizing PV system performance.

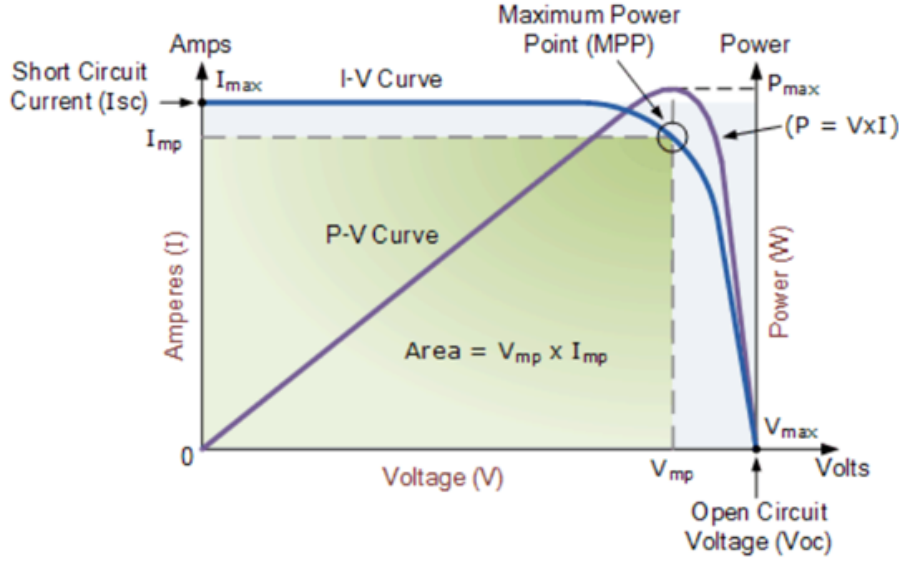


Figure 1.11: I-V and P-V Curves
[36]

3. Efficiency of a PV cell

The efficiency of a PV cell is simply the amount of electrical power coming out of the cell compared to the energy from the light shining on it, which indicates how effective the cell is at converting energy from one form to the other. The amount of electricity produced from PV cells depends on the characteristics (such as intensity and wavelengths) of the light available and multiple performance attributes of the cell. [37]

$$\eta_{\text{cell}} = \frac{P_{\text{cell}}}{I \times A_{\text{cell}}} \quad (1.2)$$

where:

- η_{cell} is the efficiency of the photovoltaic cell.
- P_{cell} is the output power of the photovoltaic cell (W).
- I is the solar insolation or irradiance (W/m^2).
- A_{cell} is the area of the photovoltaic cell (m^2).

1.2.2 PV module

A PV module comprises multiple photovoltaic (PV) cells connected in series, parallel, or a combination of both (series-parallel) to achieve the desired voltage and current levels. In a series connection, the voltage adds up while the current remains constant. In contrast, a parallel connection increases the current while maintaining the same voltage. The series-parallel configuration enables optimization of both voltage and current to meet specific power output requirements. Typical module configurations include 36, 60, or 72 cells connected in series to produce the required voltage for practical applications.

Key parameters defining a PV module's performance include:

- **Nominal Power (P_{max}):** The maximum power output under standard test conditions (STC), typically $1000 \text{ W}/\text{m}^2$ irradiance, 25°C cell temperature, and 1.5 air mass.

- **Efficiency:** The ratio of electrical power output to solar power input, indicating the module's effectiveness in converting sunlight into electricity.
- **Temperature Coefficient:** The rate at which the module's power output decreases with increasing temperature, often expressed as a percentage per degree Celsius.



Figure 1.12: PV module
[38]

1.2.3 PV array

A PV array is a collection of interconnected PV modules designed to generate electricity. Modules are connected in series to increase voltage or in parallel to increase current, enabling the array to meet specific power requirements. Key factors like shading, orientation, and tilt angle must be optimized to maximize sunlight exposure and system efficiency.

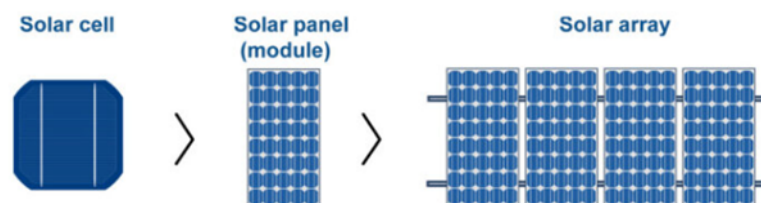


Figure 1.13: PV array
[39]

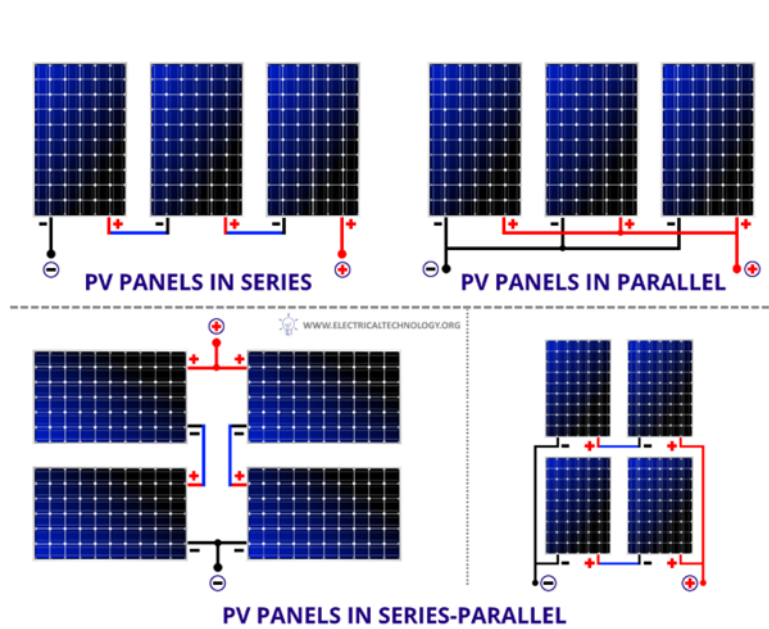


Figure 1.14: Grouping of PV modules
[40]

1.2.4 Influence of weather conditions variation on PV module parameters

1. Effect of irradiation :

The figure below illustrates the variation of the photovoltaic cell's current and power as a function of voltage for different levels of irradiation. The graph reveals that the short-circuit current (I_{sc}) varies proportionally to the irradiation, increasing as sunlight intensity rises. In contrast, the open-circuit voltage (V_{oc}) remains relatively stable, showing only minor changes with varying irradiation levels. Additionally, the power curves exhibit distinct maximum power points (MPP), which shift as irradiation changes for a given temperature. These points represent the optimal operating conditions where the module generates its maximum power output. This behavior highlights the critical role of irradiation in determining the current and power output of a PV module, while the voltage remains largely unaffected. [41]

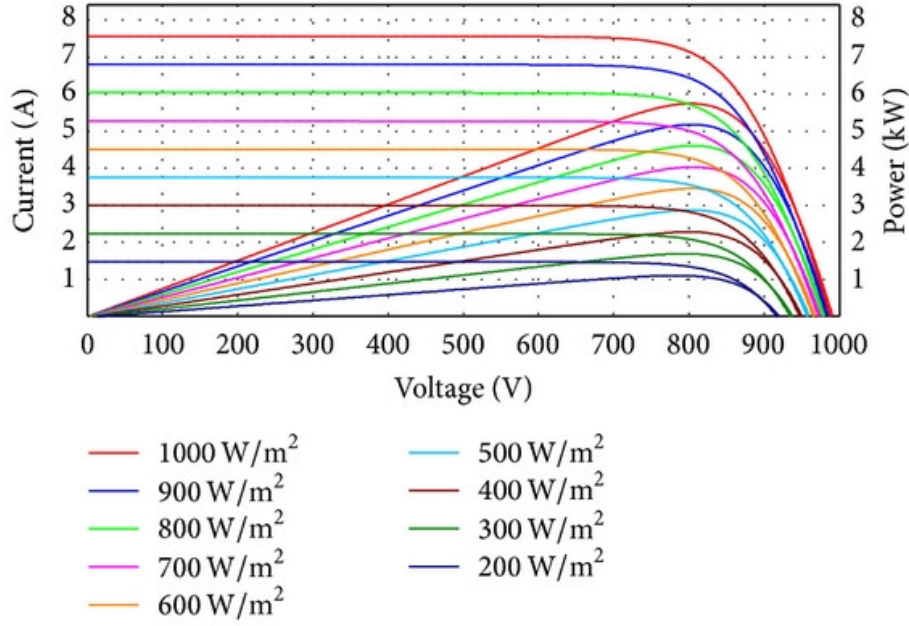


Figure 1.15: Effect of irradiation
[42]

2. Effect of temperature :

The efficiency of PV modules is highly dependent on temperature. As shown in Figure I.22, higher temperatures reduce the open-circuit voltage (V_{oc}), decreasing efficiency due to increased semiconductor resistance. Conversely, cooler temperatures improve efficiency by enhancing voltage output. While the short-circuit current (I_{sc}) remains relatively stable, temperature management is crucial for optimizing module performance and maintaining power output. [41]

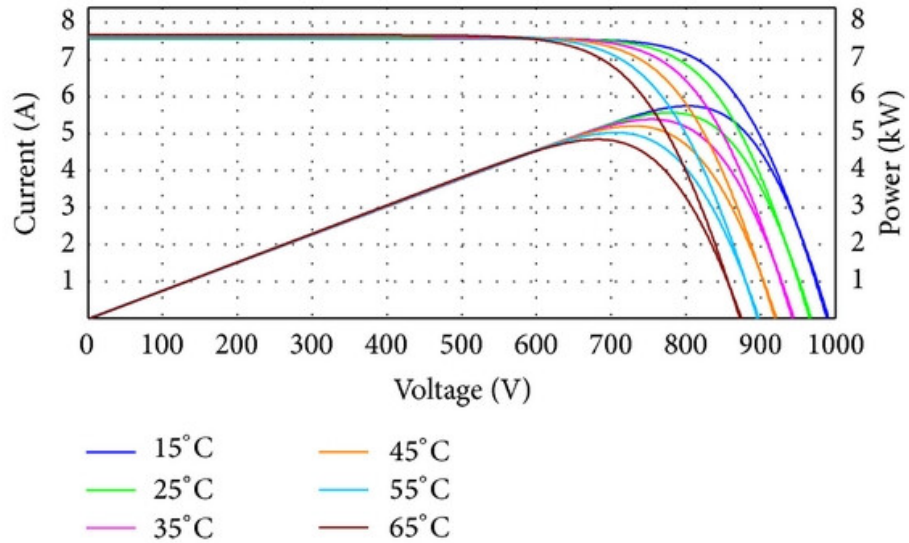


Figure 1.16: Effect of temperature
[42]

3. **Effect of dirt and dust :** The accumulation of dirt and dust on the surface of PV modules reduces sunlight absorption, leading to a decline in power output. Over time,

this buildup can significantly impact the system's efficiency. Regular cleaning is essential to maintain optimal performance and ensure the modules operate at their full potential. [43]

4. **Effect of shading :** Even partial shading on a PV module can significantly reduce its power output, as it affects the entire module's performance. Shading from trees, buildings, or other obstructions can create inefficiencies, lowering overall energy production. Proper placement of the modules and minimizing shading obstructions are critical to maximizing sunlight exposure and ensuring optimal system performance. [43]

1.2.5 Types of PV systems

Here are the main types of photovoltaic (PV) systems:

- ✓ **Grid-Tied Systems :** Grid-tied systems connect directly to the electrical grid and do not require batteries. They supply excess power to the grid through net metering, which reduces electricity bills, and draw power from the grid when solar generation is insufficient. These systems are cost-effective and require minimal maintenance, but they rely on the grid for backup power and do not work during outages for safety reasons. Common applications include residential, commercial, and utility-scale projects.
- ✓ **Off-Grid Systems :** Off-grid systems operate independently from the grid, using batteries to store excess solar energy for use during low sunlight periods. They provide energy independence and are ideal for remote areas without grid access. However, they have high upfront costs due to batteries and charge controllers, require maintenance, and are limited by battery capacity.
- ✓ **Hybrid Systems :** Hybrid systems combine grid-tied and off-grid technologies, using both batteries and grid connections. They provide backup power during outages and allow energy use from stored solar during peak hours, reducing costs. While flexible and reliable, hybrid systems are expensive to install, complex to maintain, and require periodic battery replacement.
- ✓ **Building Integrated Photovoltaics (BIPV) :** BIPV systems integrate PV modules into building materials like roofs, windows, or facades, combining energy generation with architectural design. They save space, enhance aesthetics, and may offer insulation benefits. However, they are costly to install, less efficient than traditional PV systems, and require specialized installation.

1.2.6 MPPT control algorithms

Maximum Power Point Tracking (MPPT) is used in PV systems to ensure solar panels operate at their maximum power output under varying conditions like changing sunlight and temperature. By adjusting the voltage and current via a control loop, MPPT keeps the panels at their peak power point. Common algorithms include Perturb and Observe, Incremental Conductance, and Fuzzy Logic Control, which vary in speed and tracking efficiency under different weather conditions.

1.2.6.1 Conventional methods

Conventional MPPT methods, like Constant Voltage (CV), Open Voltage (OV), Short Circuit Current (SC), Perturb and Observe (P&O), and Incremental Conductance (IC), rely on simple algorithms and mathematical principles. They are cost-effective and easy to implement. For example, the CV and OV methods use basic voltage measurements to approximate the maximum power point, while P&O and IC rely on iterative algorithms that adjust operating points based on real-time feedback of voltage and current, making them suitable for standalone systems. However, these methods often struggle in dynamic environments, such as under shading or temperature fluctuations, and may exhibit slower tracking or oscillations around the maximum power point.

1.2.6.1.1 Perturb and Observe (P&O)

The Perturb and Observe (P&O) algorithm adjusts the voltage of a PV system and observes the change in power output. If increasing the voltage raises power, the system is on the left of the Maximum Power Point (MPP) and continues incrementing voltage. If power decreases, the system is on the right of the MPP and reduces voltage. This iterative process ensures the system operates near the MPP, optimizing power generation. This algorithm is simple, cost-effective, and easy to implement but suffers from continuous oscillations around the MPP and struggles to track it during rapid changes in insolation.

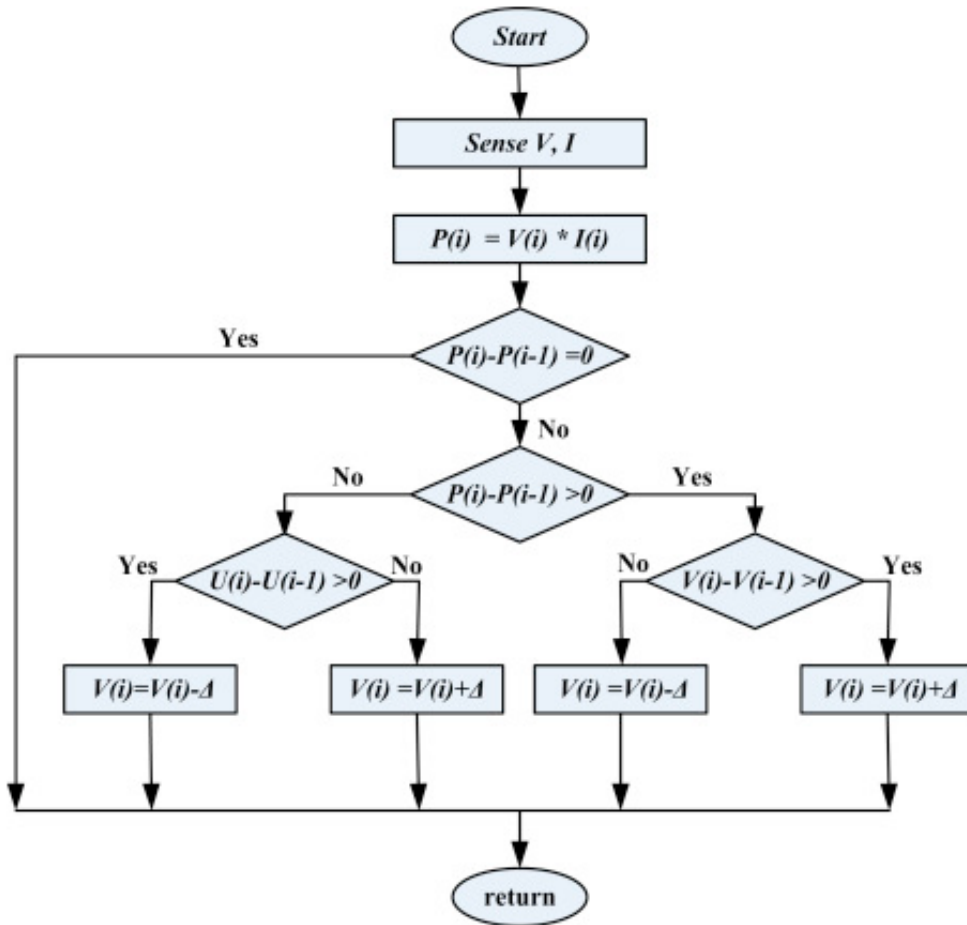


Figure 1.17: Flowchart of Perturb and Observe (P&O) method algorithm [44]

1.2.6.1.2 Incremental conductance

The incremental conductance (INC) method is one of the conventional and widely used methods for MPPT. This method relies on the point that the slope of the power-voltage curve is zero when the output power is maximum. If this slope is positive, the voltage needs to be incremented and if it is negative, the voltage needs to be decremented.

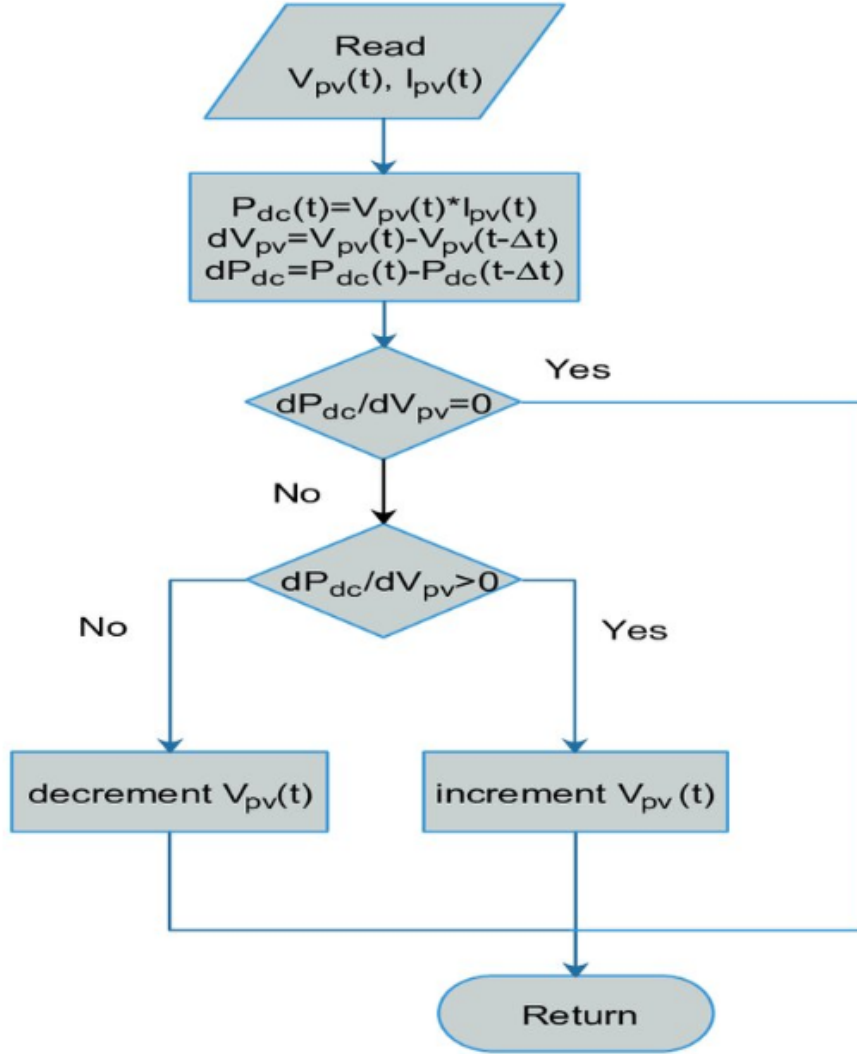


Figure 1.18: Flowchart of incremental conductance (INC) method algorithm [45]

1.2.6.1.3 Hill Climbing (HC)

Hill climbing algorithm is a local search algorithm which continuously moves in the direction of increasing elevation/value to find the peak of the mountain or best solution to the problem. It terminates when it reaches a peak value where no neighbor has a higher value. [46]

1.2.6.2 Artificial Intelligence-Based Methods

Intelligent MPPT methods, such as Fuzzy Logic and Neural Networks, use advanced AI techniques to handle complex and dynamic conditions with higher precision. They analyze multiple

parameters and adapt to changes efficiently, making them ideal for grid-connected systems, solar vehicles, and large-scale applications. While they deliver superior performance, these methods are more expensive and complex, requiring advanced sensors and computational capabilities.

1.2.6.2.1 Fuzzy logic controller (FLC)

Fuzzy Logic (FL) offers several advantages over other controllers: it does not require an exact mathematical model, can handle non-accurate input values, and effectively manages nonlinear systems. FL can calculate the perturbed voltage needed to reach the Maximum Power Point (MPP). The inputs for the proposed Fuzzy Logic Controller (FLC) are the change in power (ΔP) and the change in voltage (ΔV). [47]

1.2.6.3 Energy Performance and Cost Comparison of MPPT Techniques

(MPPT) techniques are diverse and vary significantly in terms of complexity, cost, tracking speed, range of effectiveness, hardware requirements, and popularity. Each method offers unique advantages and is suited to specific applications, from simple stand-alone systems to complex grid-connected setups. The table below provides a detailed comparison of selected MPPT techniques.

Technique	Control Complexity	Sensed Params	Add. Comp.	Sensor Cost	MCU Cost	Efficiency
Constant Voltage	Simple	V	Absent	Low	Absent/Low	94.46%
Hill Climbing	Med	V, I	Absent	Med	Low/Med	95.00%
P&O	Med	V, I	Absent	Med	Low	97.58%
InCond	Med	V, I	Absent	Med/High	Med/High	98.53%
Fuzzy Logic	Cpx	V or I	Absent	Med/High	Med/High	Over 99%

Table 1.2: Comparison of MPPT Techniques with Reported Efficiencies

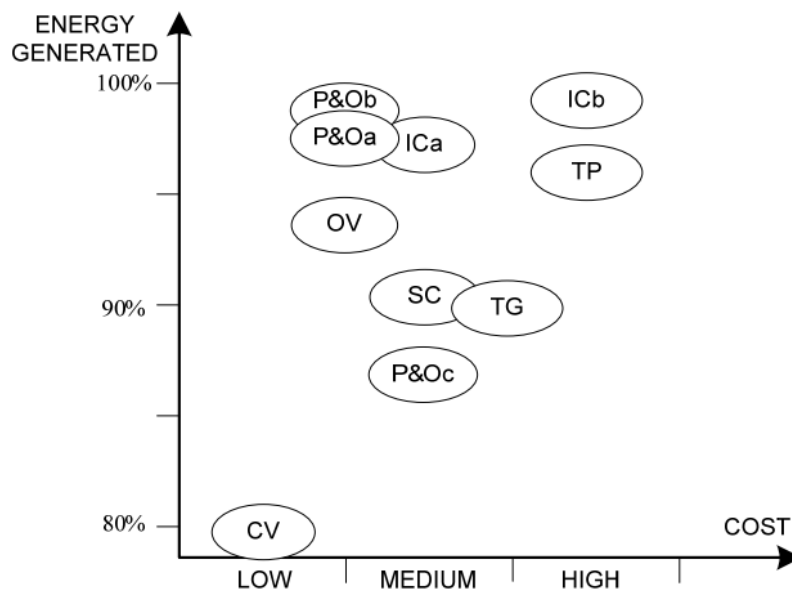


Figure 1.19: Comparison of MPPT Techniques Based on Energy Efficiency and Cost [48]

From the analysis of MPPT techniques based on energy efficiency, cost, and implementation complexity, we can conclude that:

- P&O and Incremental Conductance (IC) algorithms are among the most efficient methods, achieving efficiencies of 97.58% and 98.53%, respectively.
- Both techniques balance medium control complexity and cost while providing high energy yields, making them practical for a variety of applications.
- P&O and IC methods do not require additional static switches, reducing overall system costs and making them simpler to implement compared to methods such as Fuzzy Logic or Neural Networks.
- While Fuzzy Logic offers efficiency exceeding 99%, its complexity and cost make it less accessible for low- to medium-budget systems.

Among these techniques, P&O emerges as the most suitable choice due to its simplicity, high efficiency, and low cost of implementation. It is particularly advantageous for stand-alone systems where cost-effectiveness and reliability are critical.

1.3 Review of solar PV water pumping systems (SPVWPS)

1.3.1 Working Principle of SPVWPS

SPVWPS use electricity generated by photovoltaic panels to operate a water pump. Solar energy is converted into electrical energy by PV cells, which powers a motor (DC or AC) via a controller. The motor drives the pump, converting electrical energy into hydraulic energy to lift water. Storage components—such as batteries for electricity or tanks for water—can be included for continuous operation. System configuration depends on specific needs like required head and flow rate, with pump and panel selection tailored accordingly. The system's capacity is governed by three main parameters: pressure, flow, and input power. For design, pressure reflects the elevation difference between the water source and the storage tank, and the PV array must supply enough power to meet the pump's demand. [50]

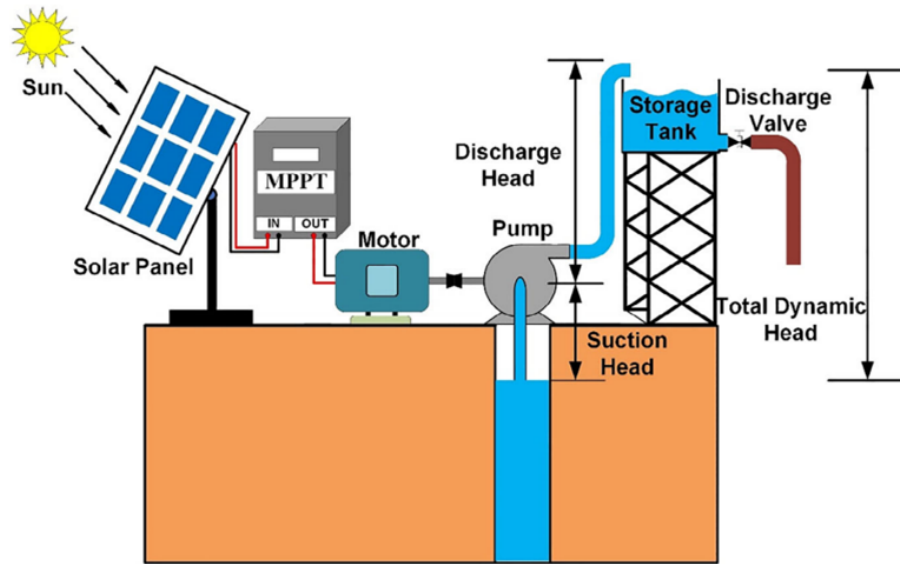


Figure 1.20: Working Principle of SPVWPS
[51]

1.3.2 Components of SPVWPS

It consists of three main components: the PV system, a power control system, and a dynamic system with a motor and pump. [52]

1. **Photovoltaic generator:** This is the power-generating unit made up of solar cells arranged into modules and panels, converting sunlight into electrical energy. The panels can be configured in series or parallel depending on the voltage and power requirements. Tracking systems may be integrated to follow the sun's path, enhancing energy capture, while optimized tilt angles improve performance based on the geographical location.
2. **Power Control System:** This system ensures the efficient operation and management of power:
 - **Charge Controllers:** Regulate the charging and discharging of batteries, preventing overcharging and deep discharge. MPPT-enabled controllers optimize energy extraction by adjusting the load to operate the array at its maximum power point.
 - **Inverters:** Convert DC electricity generated by the photovoltaic array into AC electricity, enabling compatibility with AC motors and other devices.
 - **Interconnections:** Comprise switches, cables, and connectors that ensure smooth energy flow and system integration.
3. **Dynamic System:** This includes the motor and pump that perform the actual water pumping:
 - **Motor:** Converts electrical energy into mechanical energy, powering the pump.
 - **Pump:** Converts mechanical energy into hydraulic energy to pump water. The selection of the pump is based on the discharge and head of water. Solar pumps are selected as per the rated power and accessories added as filters, float valves, switches to perform efficiently. Solar pumps are manufactured by low lead marine

grade bronze and stainless steel and are designed corrosion and maintenance-free to work in a harsh environment with a long life span of working.

4. Storage Components:

- **Battery Storage:** Stores electrical energy for use during periods of low sunlight or at night, ensuring continuous operation.
- **Water Reservoirs:** Store water pumped during the day for use during non-operational hours, reducing dependence on continuous system activity.

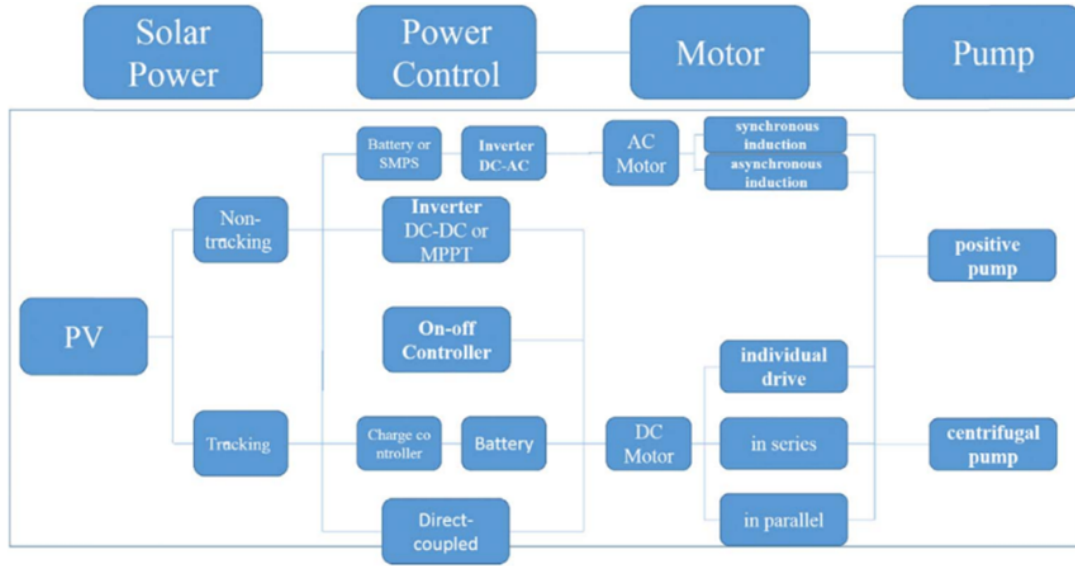


Figure 1.21: Components of SPVWPS
[52]

1.3.3 Classification of SPVWPS

Solar photovoltaic water pumping systems (SPVWPS) can be broadly classified based on energy storage, type of electrical input, and pump configuration.

1.3.3.1 Based on Energy Storage

- **Battery-coupled:** PV panels charge batteries, which then power the pump. This enables operation during low sunlight or at night, but increases cost and complexity due to storage and conversion losses. [51]

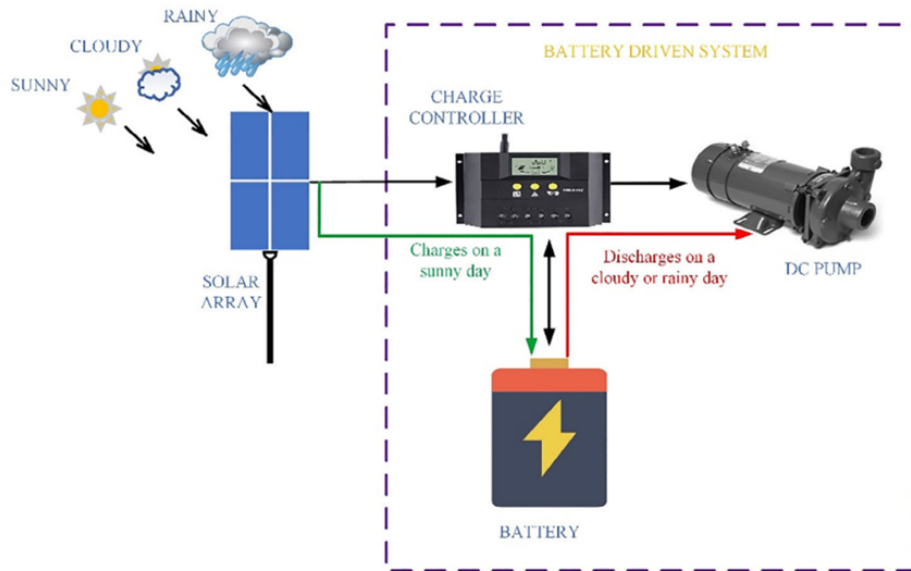


Figure 1.22: Battery-coupled SPVWPS
[51]

- **Direct-coupled:** The pump runs directly on PV power. This setup is simple and efficient during sunny periods but cannot operate at night or in low irradiation. Larger water tanks are often used to store excess water. [51]

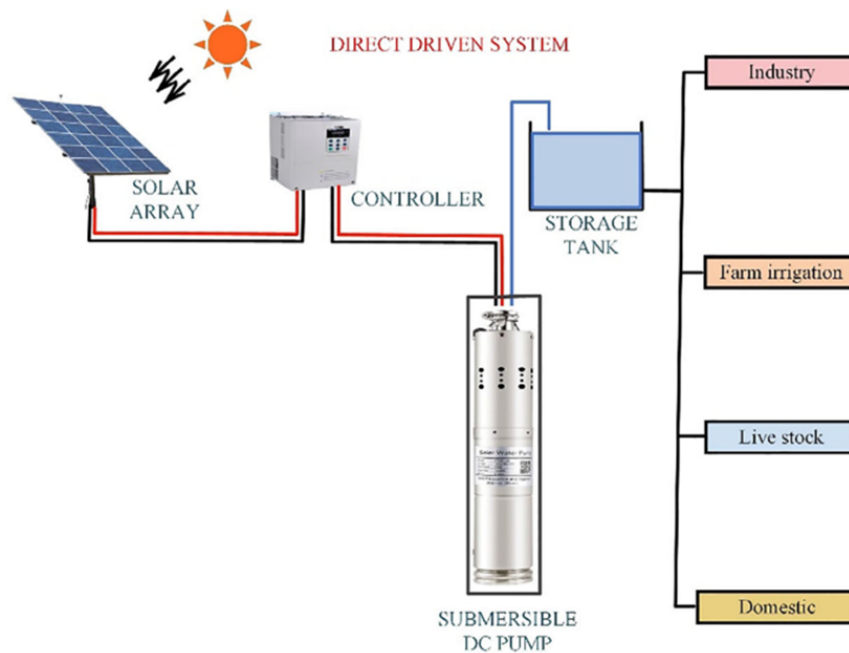


Figure 1.23: Direct-coupled SPVWPS
[51]

These configurations are off-grid and particularly suitable for remote areas with limited or no access to electricity, improving irrigation and water access in rural regions. [51]

1.3.3.2 Based on Electric Power Input

- **DC SPVWPS:** Use DC motors, typically brushless for higher efficiency and lower maintenance. [53]

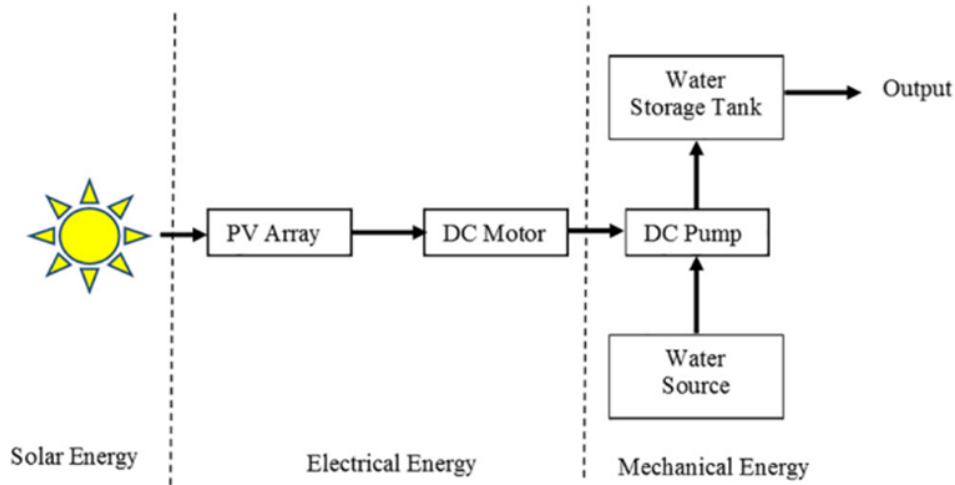


Figure 1.24: DC-powered SPVWPS
[54]

- **AC SPVWPS:** Use inverters to drive AC motors. Though slightly less efficient and more costly, this setup allows operation with grid backup. [53]

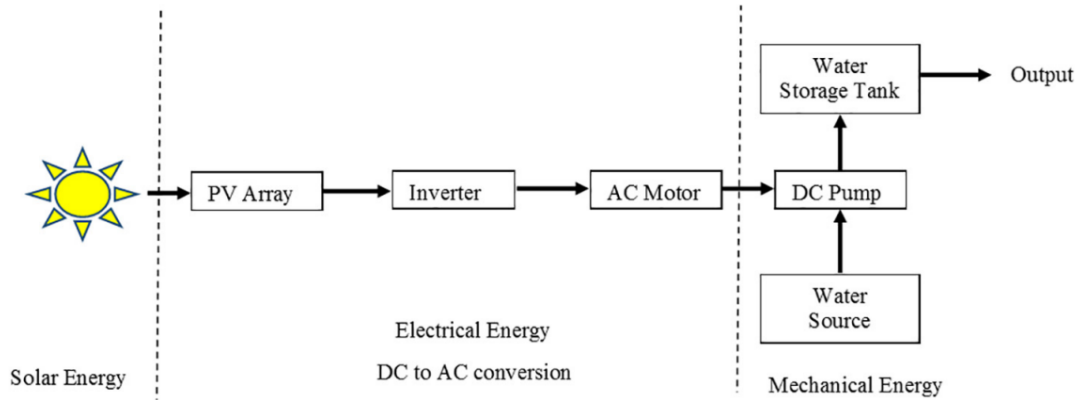


Figure 1.25: AC-powered SPVWPS
[54]

1.3.3.3 Based on Pump Type and Configuration

(a) By Application:

- **Submersible Pumps:** Installed below the water surface for deep wells and high-head applications.
- **Surface Pumps:** Used for shallow water sources, suitable for high flow but limited head.
- **Floating Pumps:** Portable pumps for reservoirs and open wells, with built-in protection against dry running. [53]

(b) By Operating Principle:

- **Dynamic Pumps:** Centrifugal and axial flow pumps convert velocity into pressure, ideal for shallow to medium lifts.
- **Positive Displacement Pumps:** Screw and piston types, efficient for high-head, low-flow cases, but require more complex control. [51]

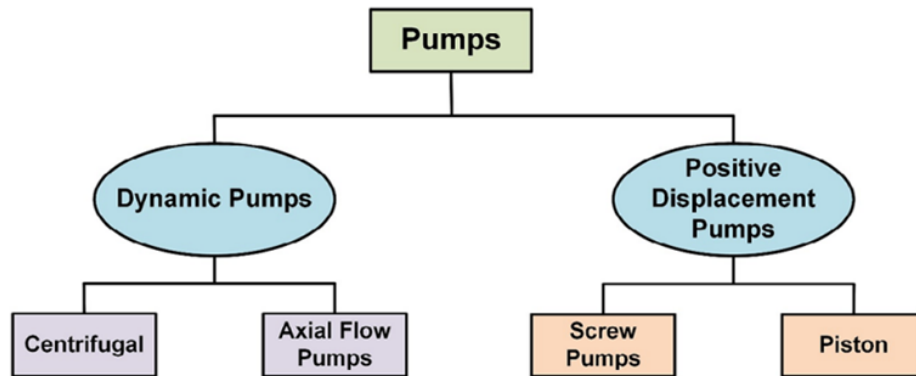


Figure 1.26: Pump types by operating principle [51]

(c) By Installation:

- **Surface-mounted Sets:** Easy to install and maintain but limited to shallow depths.
- **Deep-well Sets:** Installed below the water surface, ideal for deep applications and compatible with both AC and DC motors. [53]

This classification helps identify the most appropriate SPVWPS based on available solar resources, water demand, and site conditions.

1.3.4 SPVWPS storage techniques :

To pump water using a photovoltaic system, two techniques are possible depending on the type of storage: The first technique, with hydraulic storage, involves consuming solar energy in real-time and requires a water reservoir for storage. The second technique involves using energy storage, accomplished through the use of batteries. Energy is stored during the day and can be used later to pump water. [55]

- **Hydraulic storage technique :**

Also known as “pumping with the sun,” involves using solar energy in real-time to pump water into a reservoir during the day when sunlight is abundant. The stored water can later be distributed, often using gravity, to meet water needs during periods without sunlight. This method is simple, reliable, and cost-effective. Water reservoirs can be locally constructed, require minimal maintenance, and are easy to repair, making this solution particularly suitable for remote or rural areas.

- **Electrical storage technique :**

This technique uses batteries to store energy produced by the PV system during the day. This stored energy can then power the pump even when sunlight is unavailable, ensuring a steady water flow and continuous operation. While this approach offers greater flexibility, it has significant drawbacks, including higher costs, reduced reliability, and increased maintenance. Batteries require regular monitoring, frequent replacement, and careful management of charge and discharge cycles, which can make the system complex and less durable over time.

In summary, hydraulic storage is often favored for its simplicity and low maintenance, while electrical storage is useful when stable, round-the-clock operation is critical, despite its higher cost and maintenance requirements.

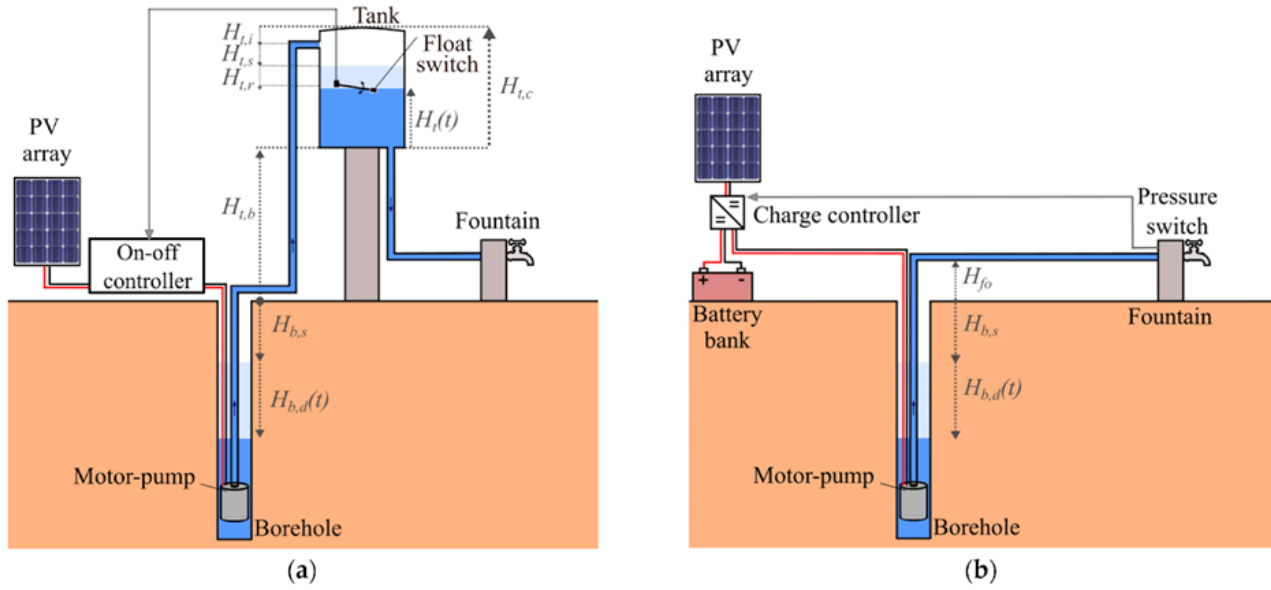


Figure 1.27: (a) Hydraulic storage technique, (b) Electrical storage technique [55]

1.3.5 Advantages of SPVWPS[52]

1. **Cost-Effective Over Time :**

- Negligible operating costs, as no fuel is required, compared to diesel or electricity-based pumps.
- Maintenance is limited to periodic cleaning, making it cheaper than diesel pumps, which require regular servicing and fuel.

2. **Environmental Benefits :**

- Solar energy is renewable and eco-friendly.
- SPVWPS reduces harmful emissions and environmental impact.

3. **Long Lifespan :**

- Typically lasts 20–30 years, with examples of systems like the one in Sonora, Mexico, operating efficiently for over 20 years.

- Short payback periods (e.g., 4 years) with significant water-pumping capacity (equivalent to 90,000 liters of diesel annually).

4. Economic Viability :

- More economical in regions like India, with payback periods of 4–6 years.
- Lifespan of 20–25 years ensures continued benefits.

5. Declining Costs :

- PV module prices have dropped by over 80% in the last decade, making solar systems more affordable.
- Diesel and gasoline prices have risen by over 250%, increasing the economic advantage of SPVWPS.

1.3.6 Factors Affecting the Performance of SPVWPS [52]

1. High Initial Cost :

- Efficiency of polycrystalline PV cells is around 18%, requiring many modules for large-scale systems, increasing costs.
- Proper component selection (panels, inverters) and panel placement angles are critical for maximizing solar exposure.
- Adding tracking systems improves power output and shortens payback periods.

2. Controller Selection :

- Maximum Power Point (MPP) tracking controllers ensure efficient PV array operation under varying conditions.
- Charge controllers prevent battery overcharging/discharging, extending battery life.
- Matching the controller and PV module optimizes power harvesting.

3. Pump and Motor Selection:

- Pumps must be selected based on application needs (e.g., irrigation or water supply) and pressure head/discharge requirements.
- Motor choice (DC or AC) impacts system efficiency; AC motors are efficient but require inverters, introducing losses.
- Proper motor-pump matching ensures optimal system efficiency.

4. Storage Devices:

- Batteries store energy for nighttime use but require proper management to prevent deep discharge and extend lifespan.
- Water reservoirs store water for non-operating periods.
- Efficiency can be improved with a double pump scheme (high-pressure pumps in low sunlight, low-pressure pumps in abundant sunlight) and automatic switching.

Conclusion

This first chapter has laid the groundwork for understanding the key technologies involved in photovoltaic water pumping systems, with a particular focus on switched capacitor multilevel inverters (SCMLIs). We began by exploring the basic principles and benefits of PV systems as a sustainable energy source, especially in off-grid and rural contexts where reliable access to electricity remains a challenge.

Through the integration of SCMLIs—which offer multiple voltage levels, compact design, and enhanced efficiency—the conversion of solar energy into electrical energy becomes more effective and economically viable. These inverters have shown promising potential due to their structural simplicity, high voltage gain, and reduced harmonic distortion, making them particularly well-suited for PV-driven applications such as water pumping.

A key aspect discussed in this chapter is the synergy between SCMLIs and photovoltaic sources. The inherently variable nature of PV energy complements the operation of SC-based inverters, which can self-boost voltage levels without relying on bulky inductive components. In fact, integrating a PV source helps mitigate some of the limitations of SCMLIs—particularly by enabling direct DC input at variable voltage levels, thus reducing the need for conventional front-end converters and improving overall system compactness and energy efficiency.

Moreover, the importance of addressing technical challenges—such as managing inrush currents and ensuring system stability—was discussed, alongside various modulation and control strategies developed to enhance the performance of SCMLIs. The growing interest in these inverter topologies reflects a broader movement toward cleaner, more decentralized energy solutions.

By consolidating the theoretical foundations of PV systems, SCMLIs, and their role in solar-powered pumping, this chapter provides a clear starting point for the practical modeling and simulation work that follows in the next stages of this study.

Chapter 2

Presentation of the proposed switched capacitor inverter topology and the hydraulic circuit modeling

Introduction

After presenting the theoretical background and motivation for multilevel inverter technologies in photovoltaic (PV) water pumping applications, this chapter introduces the core components of the system developed in this study. It focuses on the detailed description of the proposed three-phase switched capacitor inverter (SCI) topology, as well as the modeling of the hydraulic subsystem driven by the induction motor.

The chapter begins with the presentation of the inverter structure, its switching strategy, and its different operating modes. The inherent voltage-boosting capability of the SCI is discussed, highlighting its ability to generate multiple voltage levels without the use of magnetic components. Each mode of operation is explained, with reference to the voltage distribution across the switched-capacitor cells.

Next, the chapter introduces the Space Vector Modulation (SVM) technique adapted to the proposed multilevel inverter. This modulation approach is employed to generate appropriate switching sequences, reduce harmonic distortion, and improve output waveform quality. The specific implementation of SVM in the context of the SCI is described, including the introduction of new virtual voltage vectors to enable smooth and efficient multilevel voltage synthesis.

The second part of the chapter addresses the modeling of the hydraulic system, starting with the parameterization of the pump based on manufacturer data and performance curves. The hydraulic circuit is then built to replicate real-world fluid dynamics, allowing a realistic representation of the mechanical load applied to the motor during operation.

Together, these elements constitute the physical foundation of the photovoltaic water pumping system. This framework sets the stage for the implementation of control strategies and simulation-based performance analysis, which will be explored in the next chapter.

2.1 Proposed topology

The proposed topology consists of a three-stage cascaded switched capacitor (SC) converter integrated with a three-phase voltage source inverter (VSI). Each SC circuit is connected to the input voltage V_{DC} through a diode D_i , as illustrated in Fig. 1. Each SC circuit includes two switches (S_i and S'_i), which can be either IGBTs or power MOSFETs, along with a capacitor C_i . The three SC circuits are connected in cascade, with each capacitor linking to the switch of the subsequent SC stage. The positive input terminal (P) of the VSI is connected to the final capacitor of the SC circuit, while the negative terminal (N) is grounded to the input source.

To prevent short-circuiting the input voltage V_{DC} , the two switches in each SC circuit must operate in a complementary manner. This topology can generate four levels of DC voltage for the inverter, ranging from V_{DC} to $4V_{DC}$, enabling multilevel voltage at the output. The capacitors in this configuration charge to V_{DC} when connected in parallel with the input source via the diodes, and discharge when connected in series, contributing to the stepped voltage levels.[25]

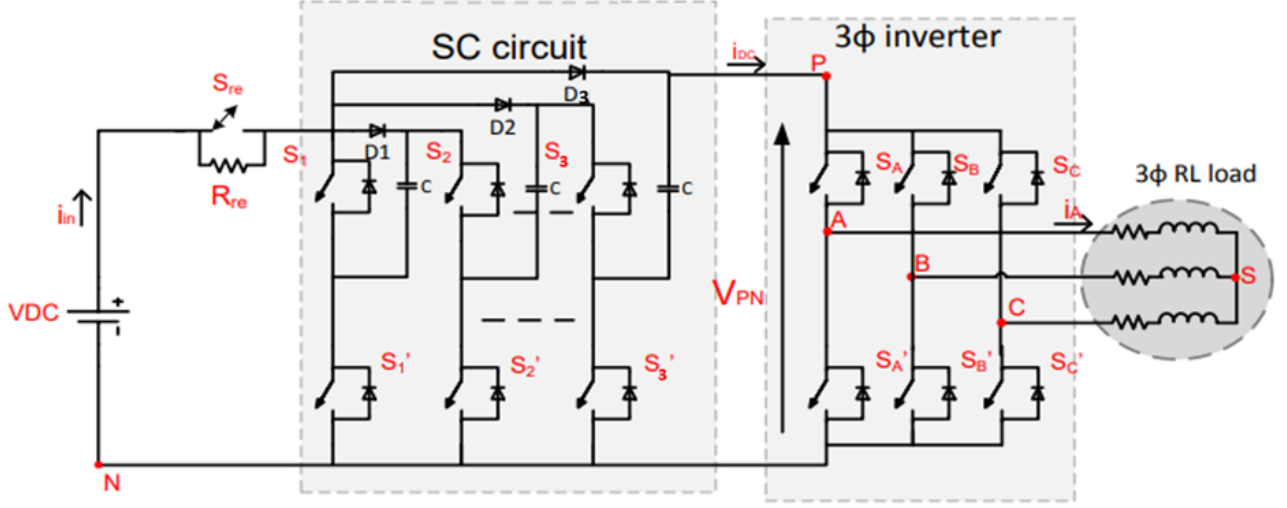


Figure 2.1: Circuit diagram of the proposed SCI topology

2.1.1 Operating modes

The proposed structure can operate in 4 modes in addition to a mode of capacitor charging as described below :

- **Mode of capacitor charging:**

In this mode, the working principle is shown in Fig. 2.2, where all upper switches (S_1 , S_2 , S_3) are turned off and the lower switches (S_1' , S_2' , S_3') are turned on. Meanwhile, all the diodes (D_1 , D_2 , D_3) are forward biased, and the capacitors (C_1 , C_2 , C_3) are charged through the recharge resistor R_{re} to limit the inrush current; i.e., they are in their charging stage. Consequently, $V_{PN} = V_{DC}$, with the three-phase inverter being turned off in this stage to accelerate the charging process and limit the input current. This mode is used only when turning on the inverter, to avoid inrush current. [25]

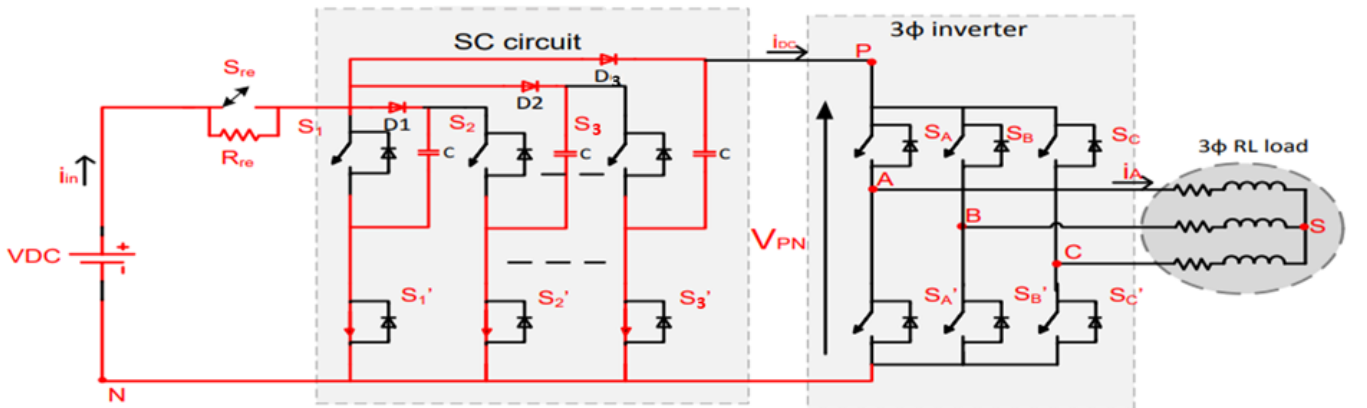


Figure 2.2: charging of capacitors mode

- **Mode 0:**

In this operating mode, as illustrated in Fig. 2.3, all the upper switches (S_1, S_2, S_3) are turned off, while the lower switches (S'_1, S'_2, S'_3) are turned on. As a result, all the diodes (D_1, D_2, D_3) are forward biased, allowing the capacitors (C_1, C_2, C_3) to charge to the input voltage V_{DC} , indicating they are in their charging state. The recharge resistor is bypassed by the switch S_{re} . Consequently, the three-phase inverter is fed by a DC voltage $V_{PN} = V_{DC}$. [25]

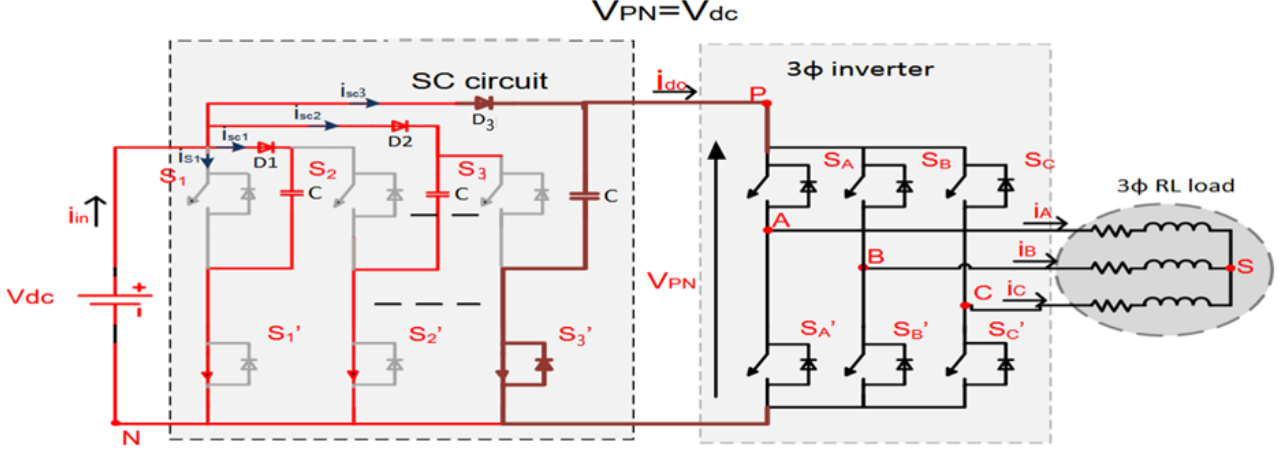


Figure 2.3: Mode 0

- **Mode 1:**

In this operating mode, as shown in Fig. 2.4, in the upper switches, only the switch S_3 is turned on, while the others (S_1, S_2) remain off. Conversely, in the lower circuit, only S'_3 is turned off, while all the other switches (S'_1, S'_2) remain on. As a result, the three-phase inverter is supplied with a DC voltage of $V_{PN} = 2V_{DC}$. The diode D_3 is reverse biased, whereas the other diodes remain forward biased. In this mode, only capacitor C_3 is in the discharging state, while the remaining capacitors continue their charging. [25]

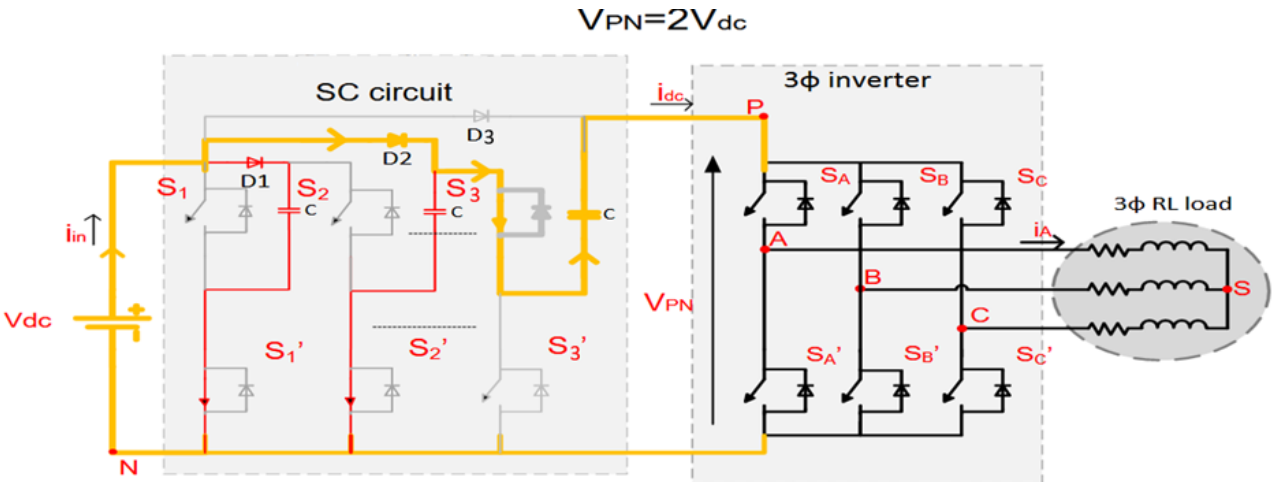


Figure 2.4: Mode 1

- **Mode 2:**

In this operating mode, as shown in Fig. 2.5, the upper switches (S_2, S_3) are turned on, while S_1 is turned off. Conversely, in the lower circuit, (S'_2, S'_3) are turned off, while S'_1 is turned on. As a result, the three-phase inverter is fed by a DC voltage $V_{PN} = 3V_{DC}$. In

this mode, the diodes (D_2, D_3) are reverse biased, whereas D_1 remains forward biased. Consequently, the capacitors (C_2, C_3) are in the discharging mode, while C_1 continues its charging phase. [25]

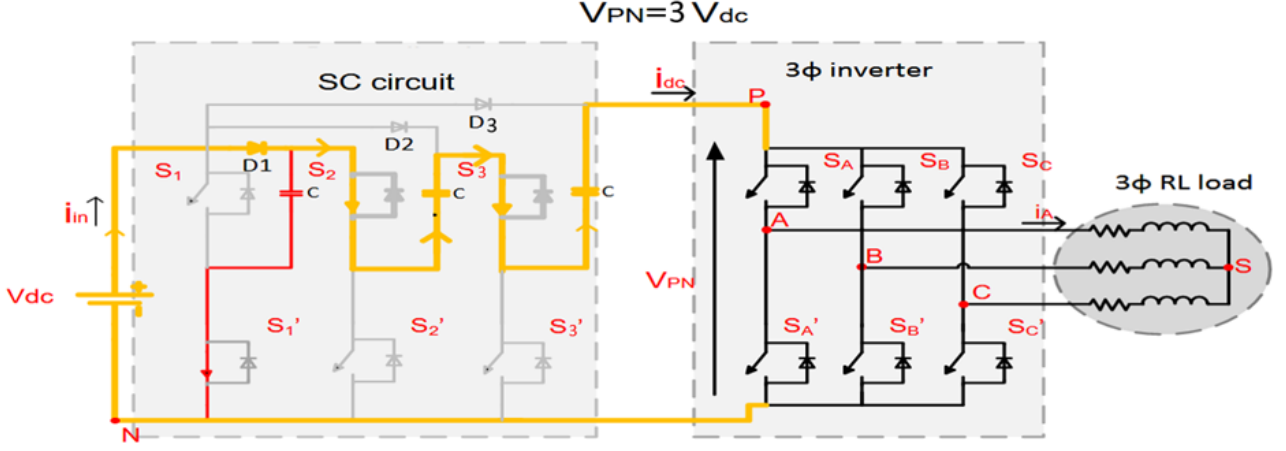


Figure 2.5: Mode 2

- **Mode 3:**

As illustrated in Fig. 2.6, this operating mode occurs when all the upper switches (S_1, S_2, S_3) are turned on, whereas the lower switches (S'_1, S'_2, S'_3) are turned off. In this mode, all the capacitors are connected in series via the switches S_i , and the three-phase inverter is fed by a DC voltage $V_{PN} = 4V_{DC}$. All the diodes (D_1, D_2, D_3) are reverse biased; therefore, all capacitors are in their discharging mode.[25]

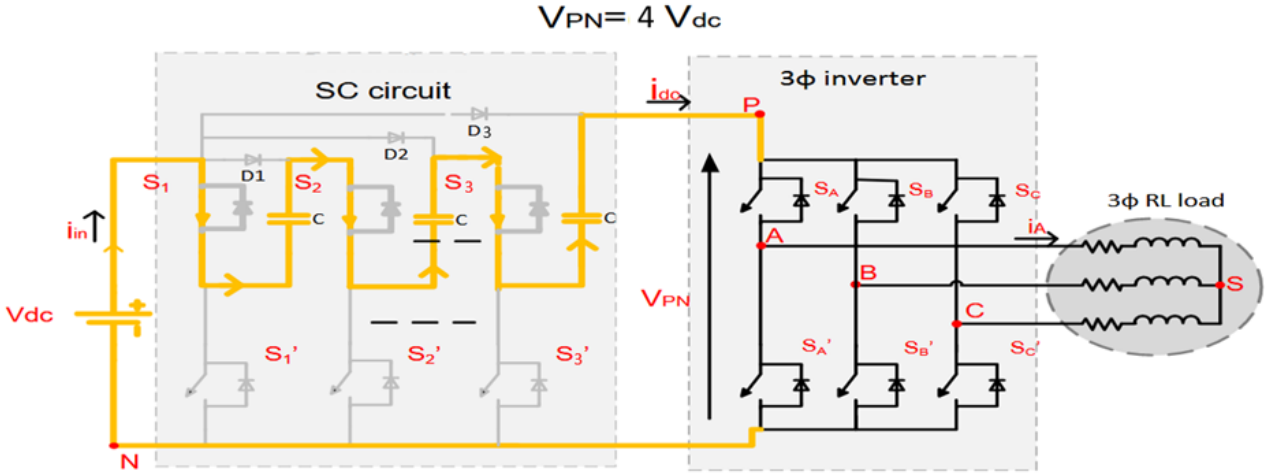


Figure 2.6: Mode 3

2.2 Space Vector Modulation Technique

2.2.1 Principle:

Space Vector Modulation (SVM) is an advanced pulse width modulation (PWM) technique used to control three-phase voltage source inverters by synthesizing a desired output voltage. Unlike traditional PWM methods, SVM represents the three-phase voltages as a single rotating space vector in a two-dimensional reference frame, allowing for more efficient control of the inverter's

switching states. By strategically selecting and combining these states, SVM ensures optimal utilization of the DC bus voltage, reduces harmonic distortion, and minimizes switching losses. This technique provides a nearly sinusoidal output, improving the performance of motor drives, renewable energy systems, and power electronic applications requiring precise and efficient modulation. Its implementation enhances the dynamic response, efficiency, and reliability of electrical systems, making it a preferred choice in modern power electronics [56]

2.2.2 Application of SVM to the proposed structure:

In this study, a modified Space Vector Modulation (SVM) strategy is developed to control the proposed topology. Due to the unique configuration of the converter, conventional SVM techniques cannot be directly applied. To overcome this limitation, an adapted SVM approach is introduced, based on the use of new virtual vectors to synthesize the reference voltage. This method ensures a multilevel output voltage while optimizing the inverter's performance by reducing the total harmonic distortion (THD) and extending the voltage ratio range. The proposed modulation strategy is particularly suited for photovoltaic applications, especially in off-grid systems, where efficient power conversion and high-quality output waveforms are essential.

Before detailing the modulation technique, it is crucial to establish the general model of the converter using switching functions, which define the relationship between the switching states and the generated output voltages. [24]

2.2.2.1 General model of the converter

In this analysis, six switching functions ($s_1, s_2, s_3, s_A, s_B, s_C$) are defined, corresponding to the switch states of the switched capacitor (SC) circuit (S_1, S_2, S_3) and the inverter (S_A, S_B, S_C), respectively. If a switch S_j is ON, its corresponding switching function is equal to 1; otherwise, it is 0. Therefore, the output voltages of the proposed topology [V_{As}, V_{Bs}, V_{Cs}] can be calculated as follows:

$$\begin{cases} V_{As} = \frac{(2s_A - s_B - s_C)}{3} (V_{dc} + s_3 V_{Sc3} + s_2 V_{Sc2} + s_1 V_{Sc1}) \\ V_{Bs} = \frac{(2s_B - s_A - s_C)}{3} (V_{dc} + s_3 V_{Sc3} + s_2 V_{Sc2} + s_1 V_{Sc1}) \\ V_{Cs} = \frac{(2s_C - s_B - s_A)}{3} (V_{dc} + s_3 V_{Sc3} + s_2 V_{Sc2} + s_1 V_{Sc1}) \end{cases} \quad (2.1)$$

If the variation of the SC capacitor voltage and the switches' voltage drops are neglected, then $V_{Scj} = V_{dc}$. The output voltage can be rewritten as follows:

$$\begin{cases} V_{As} = \frac{(2s_A - s_B - s_C)}{3} (1 + s_3 + s_2 + s_1) V_{dc} \\ V_{Bs} = \frac{(2s_B - s_A - s_C)}{3} (1 + s_3 + s_2 + s_1) V_{dc} \\ V_{Cs} = \frac{(2s_C - s_B - s_A)}{3} (1 + s_3 + s_2 + s_1) V_{dc} \end{cases} \quad (2.2)$$

2.2.2.2 Detailed working principle of the modified SVM

2.2.2.2.1 Determination of the reference voltage vector (Space vector)

The reference voltage vector, also called the space vector, represents the desired sinusoidal output voltage of the inverter and is defined as:

$$\begin{cases} V_{\text{ref}} = V_{\text{max}} e^{j\omega t} = \frac{2}{3} (V_{As} + aV_{Bs} + a^2V_{Cs}) \\ V_{\text{ref}} = \frac{2}{3} (S_{As} + aS_{Bs} + a^2S_{Cs}) V_{\text{dc}} \end{cases} \quad (2.3)$$

With: $a = e^{\frac{2\pi j}{3}}$, $a^2 = e^{\frac{4\pi j}{3}}$

V_{max} : Maximum amplitude of the vector V_{ref}

2.2.2.2.2 Determination of the sector

The sector is one of the six regions in the space vector diagram, used to determine the position of the reference voltage vector. The proposed structure of the switched capacitor inverter aims to increase the output voltage up to four times, depending on the states of the switches S1, S2, S3 at the SC cells. Therefore, each regular vector will be composed of four vectors depending on the operating mode.

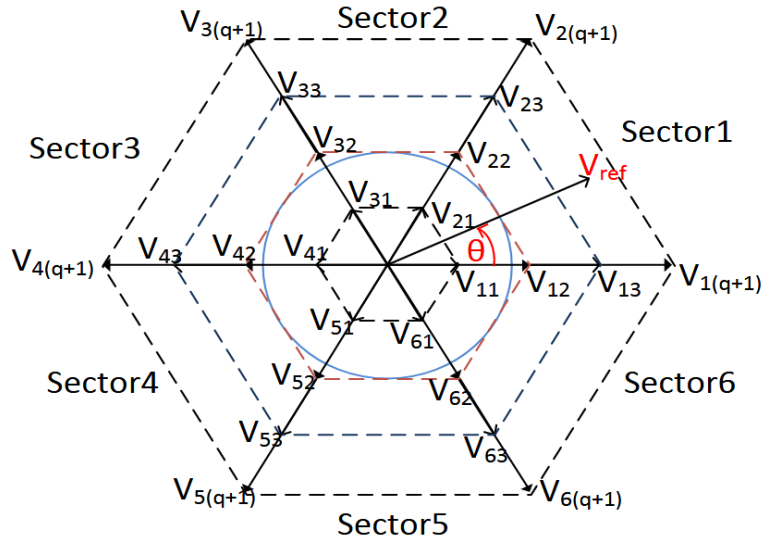


Figure 2.7: The space vector diagram of the possible output voltage

2.2.2.2.3 Determination of the region

Each sector in the voltage space diagram is subdivided into smaller regions, known as sub-sectors, to precisely determine the appropriate voltage vector for approximating the reference voltage. The selection of a region is based on the position of the reference voltage vector relative to the region boundaries. The final voltage vector is then obtained by combining two adjacent active virtual voltage vectors of the same mode within the sector and one zero vector.

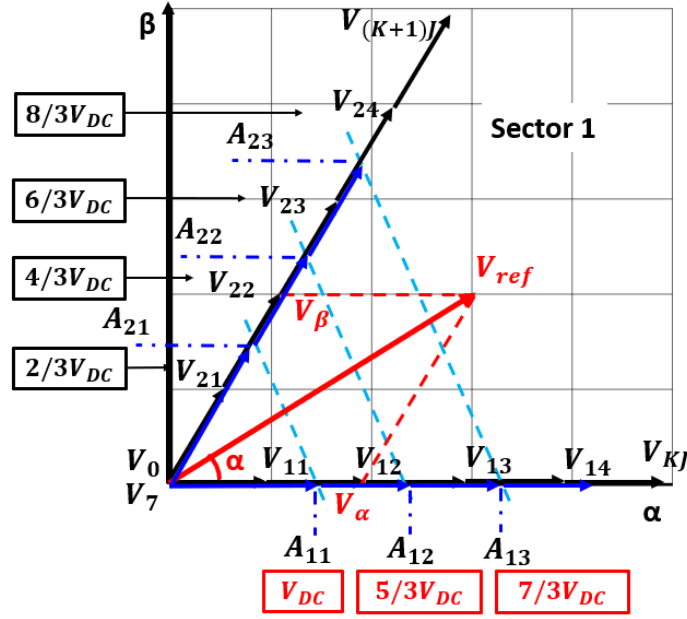


Figure 2.8: The space vector diagram of the possible virtual output voltage in SVM2 sector 1

2.2.2.2.4 Determination of the mode

The mode can be defined by the number I , which is the result of the Euclidean division of the voltage ratio by its allowed maximum 1.1:

$$I = \text{int} \left(\frac{r}{1.1} \right) \quad (2.4)$$

We define the voltage ratio as:

$$r = \frac{V_{\max}}{V_{\text{dc}}/2} \quad (2.5)$$

2.2.2.2.5 Calculation of the duty cycles

The calculation of the duty cycles is performed by the projection of V_{ref} into α , β axes as in the conventional SVM. The duty cycles for each applied active vector and zero vector are defined as follows:

$$\begin{cases} d_\alpha = m \sin \left(\frac{\pi}{3} - \alpha \right) \\ d_\beta = m \sin (\alpha) \\ d_0 = 1 - (d_\alpha + d_\beta) \end{cases} \quad (2.6)$$

α is the phase angle by the sector and m is defined as:

$$\left\{ m_v = \frac{r V_{\text{dc}}}{2 |A_{kj}| \sin(\pi/3)} \right. \quad (2.7)$$

with :

$$\left\{ |A_{kj}| = \frac{1}{3} V_{\text{dc}} + \frac{2I}{3} V_{\text{dc}} \right. \quad (2.8)$$

2.2.2.2.6 Calculation of switching times

The calculation of the switching times is based on reconstructing the space vector V_{ref} as the time-averaged sum of the three voltage vectors defining the region in which it is located. This is achieved by expressing V_{ref} as a weighted combination of these three vectors, ensuring an accurate approximation of the desired reference voltage.

Mathematically, this can be expressed as:

$$V_{\text{ref}} = d_{\alpha}V_{\alpha} + d_{\beta}V_{\beta} + d_0V_0 \quad (2.9)$$

Where: V_{α} , V_{β} and V_0 are the three voltage vectors in the region.

And: d_{α} , d_{β} , and d_0 are the duty cycles.

With:

$$\begin{cases} d_{\alpha} = \frac{T_{\alpha}}{T_s} \\ d_{\beta} = \frac{T_{\beta}}{T_s} \\ d_0 = \frac{T_0}{T_s} \end{cases} \quad (2.10)$$

And:

$$T_{\alpha} + T_{\beta} + T_0 = T_s \quad (2.11)$$

2.2.2.2.7 Selection of vectors

To minimize the number of commutations, the vectors are applied in a specific sequence, as illustrated in Fig. 2.9. Additionally, to ensure proper charging of all capacitors, mode 0 must be activated during the application of zero vectors. Fig. 2.9 also reveals that one of the gate signals of the SC circuit cannot be directly generated using a conventional center-aligned PWM. Instead, it can be obtained by using an XOR logic gate with two center-aligned PWM signals.

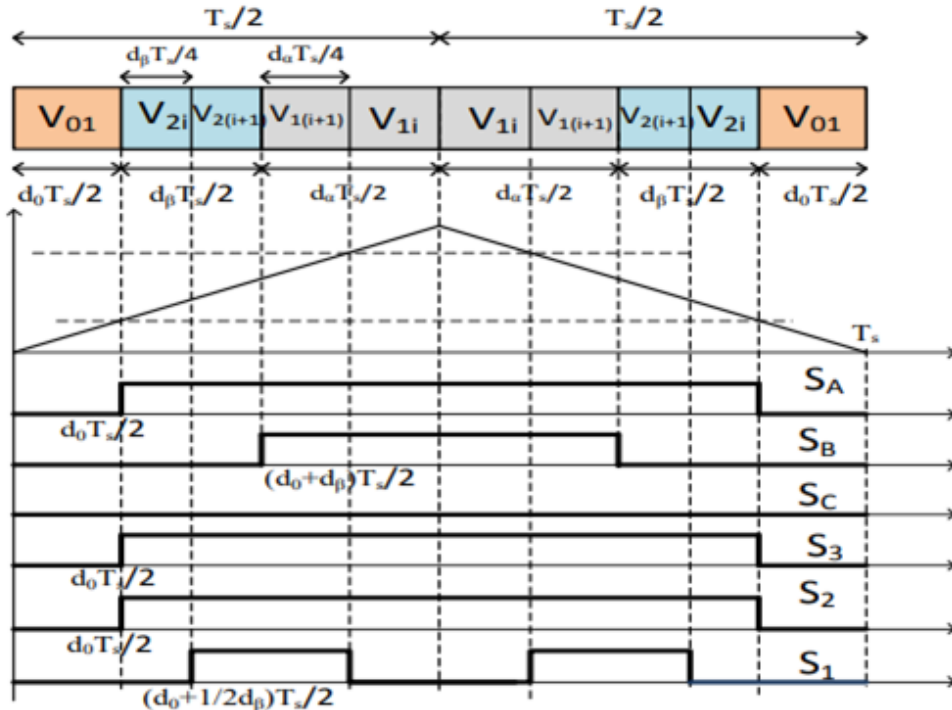


Figure 2.9: SVM2 switching sequence in case of I=3, sector1

2.3 Pump Modeling and Hydraulic Circuit

The proposed system includes a centrifugal pump driven by an asynchronous motor, supplying fluid to a hydraulic load through a network of pipes. This section focuses on modeling the hydraulic subsystem, including the pump characteristics and the associated hydraulic circuit. The main characteristics of the asynchronous machine are briefly provided to contextualize the simulation environment.

The characteristics of the asynchronous machine are as follows:

Parameter	Value
Nominal Power P_n	4 kW
Nominal Output Voltage U_n	400 V
Nominal Frequency f_n	50 Hz
Stator Resistance R_s	1.405 Ω
Inductance of the Stator and Rotor L_s, L_r	0.005839 H
Rotor Resistance R_r	1.395 Ω

Table 2.1: Asynchronous machine characteristics

A hydraulic circuit was designed and implemented to represent the mechanical load driven by the asynchronous motor. The circuit consists of a centrifugal pump, water as the working fluid, and a pipe network comprising both vertical and horizontal sections. This setup allows the simulation to capture the coupling between electrical and fluidic domains, where the torque required by the pump is determined by the flow dynamics and pressure demands of the system.

2.3.1 Hydraulic System Characteristics

A hydraulic circuit was designed to simulate a water-based system driven by a centrifugal pump. It includes horizontal and vertical pipes, with performance influenced by elevation changes and internal friction. [57] [58]

The centrifugal pump draws water from a lower reservoir (suction side) and delivers it to an upper reservoir (discharge side). The total energy the pump must supply is defined by the Total Dynamic Head (TDH)

2.3.1.1 Total Dynamic Head (TDH)

The Total Dynamic Head of a pump is defined as the pressure difference between the outlet and inlet, expressed in units of height (typically meters). It represents the maximum elevation to which the pump can raise the fluid. This parameter is critical for evaluating the pump's ability to overcome system resistances such as bends, valves, and pipe friction. The discharge head is a key factor in pump selection, as it must account for structural constraints like pipe length and diameter, lift height, and the required flow rate.

It is commonly expressed by the following equation:

$$TDH = h_s + h_d + h_f \quad (2.12)$$

Where:

- h_s : Suction head (from source to pump)
- h_d : Discharge head (from pump to outlet)
- h_f : Head losses due to friction and fittings

This configuration is commonly used to demonstrate how a centrifugal pump overcomes both elevation and resistance to maintain continuous fluid flow.

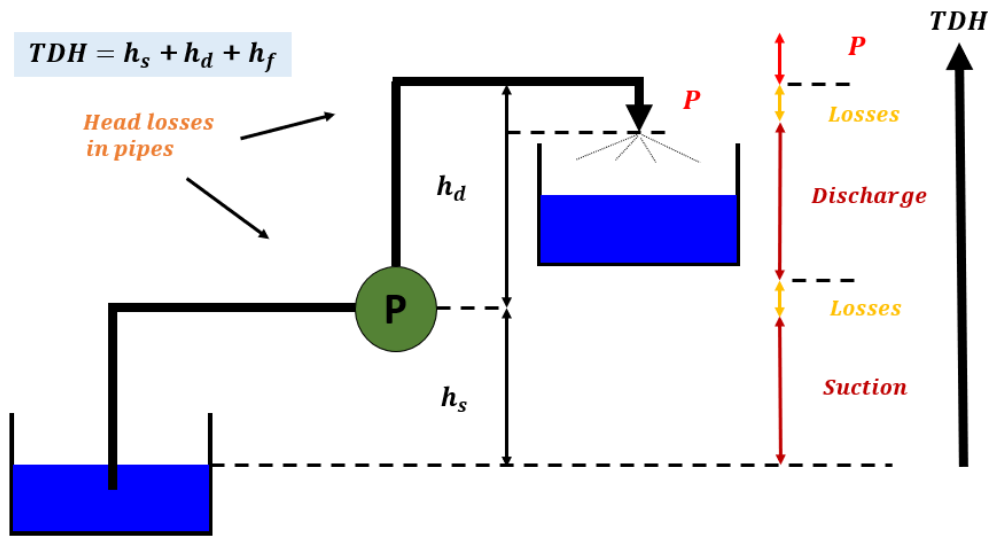


Figure 2.10: Hydraulic System schematic

2.3.1.2 Flow Rate of a Centrifugal Pump

The flow rate of a centrifugal pump refers to the volume of fluid it can transport per unit of time, typically expressed in liters per minute or cubic meters per hour. It depends on the pump's geometry, rotational speed, and fluid properties (density and viscosity). Flow rate is a critical specification, as it directly determines whether the pump can meet the system's required delivery.

2.3.1.3 Centrifugal Pump Characteristic Curves

Pump performance curves are essential tools for selecting, testing, operating, and maintaining pumps. The primary curve plots differential head versus flow rate, revealing how head output varies with flow. Manufacturers often provide additional curves for power, efficiency, and NPSH as functions of flow. Performance testing validates these specifications. Over time, process conditions—such as system resistance, infrastructure, or fluid properties—may change. In such cases, comparing the updated system requirements with existing pump curves helps determine whether current pumps remain optimal or should be replaced.

1. Head–Flow Curve (H–Q Curve)

The characteristic curve of a pump represents its ability to generate a specific flow rate as a function of the total dynamic head. The relationship between flow rate and head, at a constant rotational speed, is unique to each pump design.

Manufacturers of centrifugal pumps typically provide characteristic curves $Q(H_m)$, corresponding to the maximum and minimum available impeller diameters.

When dealing with a **centrifugal pump equipped with a radial impeller**, its hydraulic behavior can be modeled using an analytical expression that relates the *total manometric head* H_m to the *flow rate* Q and the *rotational speed* w of the pump shaft.

By considering the rotational speed as a parameter, a commonly used empirical model takes the following form:

$$H_m = C_1 w^2 - C_2 w Q - C_3 Q^2 \quad (2.13)$$

where:

- C_1, C_2, C_3 : constants specific to the pump, provided by the manufacturer,
- w : rotational speed [$rad \cdot s^{-1}$],
- Q : volumetric flow rate [m^3/s],
- H_m : total manometric head [m].

2. Power–Flow Curve (P–Q Curve)

The **power curve** of a pump is a key performance indicator that reflects how much input energy is required to maintain fluid movement across varying flow conditions. It is typically plotted with the **flow rate** Q on the x-axis and the **absorbed power** W (in kW or HP) on the y-axis. The absorbed power represents the mechanical or electrical energy drawn by the pump to overcome hydraulic resistance and maintain flow. In simplified terms, it can be expressed as:

$$W = \rho g Q H$$

where:

- ρ : fluid density (kg/m^3),
- g : gravitational acceleration ($9.81 m/s^2$),
- Q : volumetric flow rate (m^3/s),
- H : total head (m).

This represents the *hydraulic power* delivered to the fluid.

It's also known as the **Brake Horsepower (BHP)** curve when referring to the actual *mechanical power required at the pump shaft*. BHP accounts for the hydraulic load, internal losses, and pump efficiency, and is typically expressed in **kilowatts (kW)** or **horsepower (HP)**. The **BHP curve**—a form of the *Power–Flow (P–Q) curve*—usually shows an increasing trend for centrifugal pumps: as the flow rate increases, more power is needed to maintain the head. This curve is essential for *motor sizing*, *energy consumption assessment*, and ensuring *reliable and efficient operation* of the pump.

3. Efficiency–Flow Curve (–Q Curve)

The **pump efficiency curve** illustrates how efficiently a pump converts input power into hydraulic energy across a range of flow rates. Plotted as a function of the volumetric flow rate Q on the x-axis, the curve shows the efficiency η , defined as the ratio of useful hydraulic power to the absorbed mechanical power:

$$\eta = \frac{P_u}{P}$$

where:

- P_u : useful (hydraulic) output power, typically $P_u = \rho g Q H$,
- P : absorbed mechanical power at the pump shaft.

Efficiency typically increases from near zero at low flow rates, reaches a peak—often around 85%—at the *Best Efficiency Point (BEP)*, and then declines beyond that point.

Operating the pump near its BEP is critical for ensuring maximum efficiency, extending component lifespan, and minimizing vibration and mechanical wear. Conversely, operating far from the BEP results in reduced performance and may cause hydraulic instabilities, excessive heat, and mechanical stress, which, under extreme conditions, can lead to pump failure within minutes.

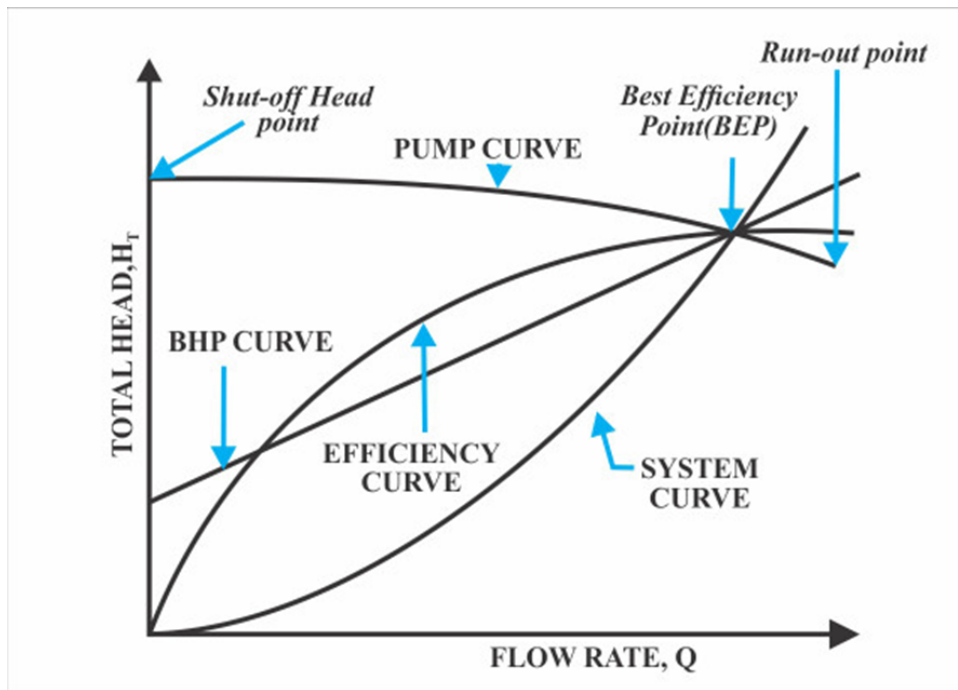


Figure 2.11: Centrifugal Pump Characteristic Curves

2.3.2 Centrifugal Pump Parameterization

The selected pump model is characterized by the following nominal specifications:

Specification	Value
Rotor Speed n	1450 RPM
Motor Nominal Power P_2	4 kW
Required Flow Rate	800 L/min (0.013 m ³ /s)
Total Dynamic Head H	9 meters

Table 2.2: Nominal specifications of the selected pump

The pump was parameterized based on experimental performance curves provided in the manufacturer's datasheet, which includes the relationship between the pressure differential and brake power versus the pump's delivery characteristics.

The pump's performance characteristics were derived by converting the head vs. flow rate curve into a pressure vs. flow rate relationship. This data was used to interpolate the mechanical torque required by the pump at each operating point, allowing for accurate dynamic modeling in the simulation environment. This ensures that the mechanical behavior of the load closely reflects the real-world characteristics of centrifugal pumping systems.

The figure below illustrates the characteristic performance curves of the centrifugal pump used in the simulation.

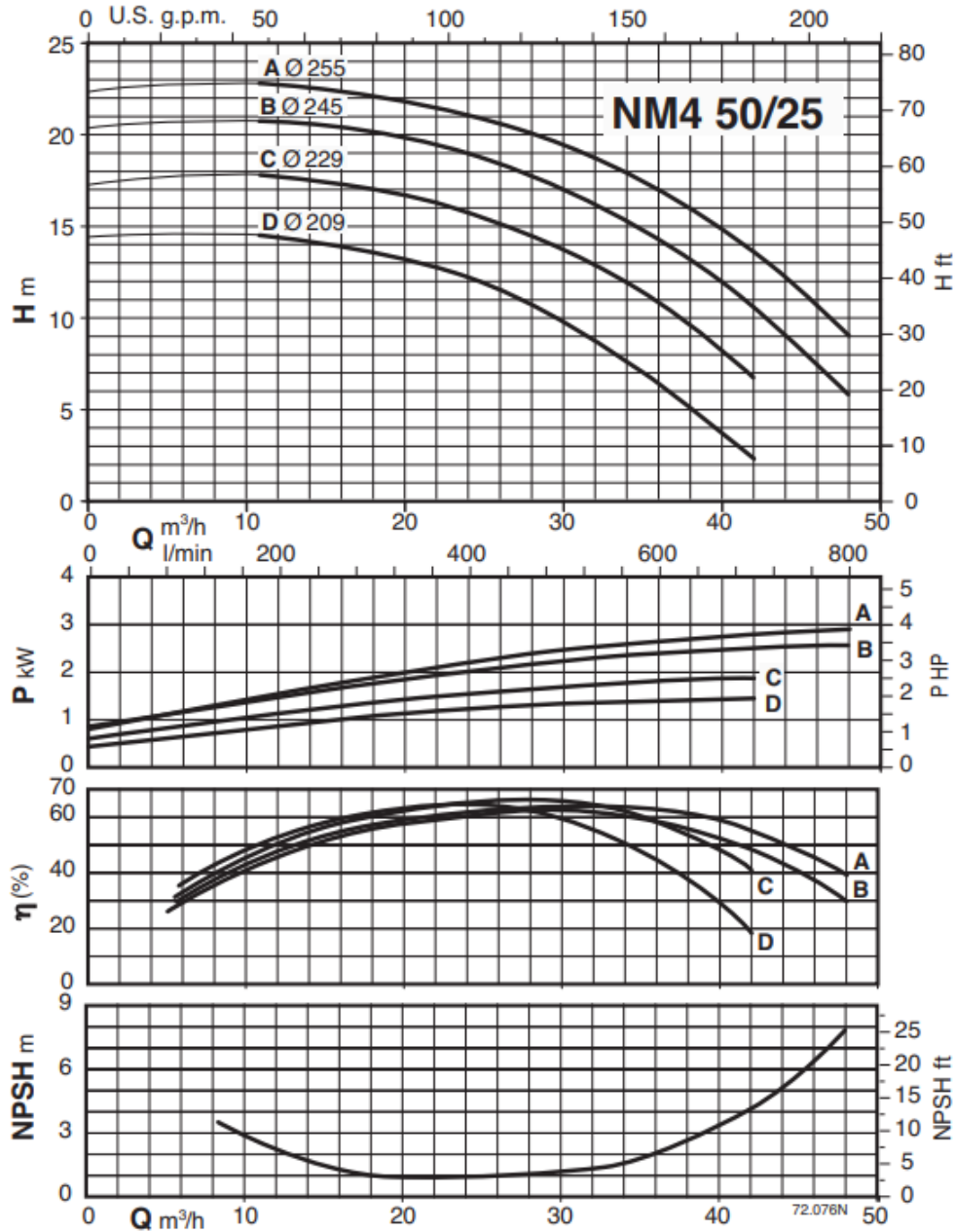


Figure 2.12: Centrifugal Pump performance curves (CALPEDA NM4 50/25A/B)

- Friction Losses

The head loss due to pipe friction was calculated using the Darcy-Weisbach equation:

$$H_f = f \cdot \frac{L}{D} \cdot \frac{v^2}{2g}$$

where:

- f is the Darcy friction factor,
- L is the pipe length,
- D is the pipe diameter,
- v is the average fluid velocity,
- g is the gravitational acceleration.

The Colebrook-White equation was solved numerically using MATLAB to determine f , yielding:

$$f = 0.015628$$

Substituting the known values gave a friction loss of:

$$H_f = 1.0695 \text{ m}$$

This value is included in the total dynamic head the pump must overcome.

- **Net Positive Suction Head (NPSH)**

To avoid cavitation, the Net Positive Suction Head (NPSH) was considered. Based on the manufacturer's performance curve, the available NPSH is:

$$\text{NPSH}_{\text{available}} = 8 \text{ m}$$

This exceeds the required NPSH under rated conditions, confirming safe operation of the pump.

- **Static Lift (noted by A in the picture above)**

The static head H_s refers to the vertical elevation that the pump must lift the fluid. It is a major component of the Total Dynamic Head (TDH) and is essential for determining the energy required to move fluid in the system.

It was calculated using the expression of the Net Positive Suction Head (NPSH), taking into account the friction losses H_f . The equation is given by:

$$\text{NPSH}_{\text{available}} = H_a - H_v - H_s - H_f$$

where:

- H_a is the atmospheric pressure head,
- H_v is the vapor pressure head,
- H_f is the friction loss in the suction line,
- H_s is the static suction lift.

Using this equation and the known values ($H_f = 1.0695 \text{ m}$, $\text{NPSH}_{\text{available}} = 8 \text{ m}$), the static lift was determined to be:

$$H_s = 1.02 \text{ m}$$

This value represents the vertical height that the fluid must be lifted from the suction tank to the pump inlet.

- **Pipe Dimensions**

The calculations performed previously, including the friction losses and static lift, were used to determine the dimensions of both the vertical and horizontal pipes in the hydraulic system. These dimensions ensure that flow rates and pressure conditions are maintained within the system's operational limits.

The pipe diameter was selected as:

$$\text{Pipe Diameter} = 3 \text{ inches}$$

Conclusion

This chapter has presented the core structural components of the photovoltaic water pumping system. First, the proposed three-phase switched capacitor inverter topology was described in detail, including its voltage boosting capabilities and multilevel output generation using a reduced number of components. The inverter's operation across different switching modes was explained, and its suitability for PV-driven applications was justified based on its compactness, modularity, and harmonic performance potential.

The chapter also introduced the use of Space Vector Modulation (SVM) tailored for the proposed topology. The inclusion of newly synthesized voltage vectors enables better switching control and improved waveform quality—crucial for efficient motor operation and reduced electromagnetic interference.

In parallel, the modeling of the hydraulic circuit was carried out, with an emphasis on realistic parameterization of the pump and the fluid flow. This model reflects the dynamic mechanical load imposed on the motor and provides a necessary link between the electrical and mechanical domains of the system.

These foundational models—electrical and hydraulic—establish the framework upon which control strategies and simulations will be applied in the next chapter, allowing for a complete evaluation of system performance under various operating conditions.

Chapter 3

Simulation and Control of a
PV-Powered water pumping system
using the proposed switched capacitor
inverter topology

Introduction

After the modeling of the PV pumping system was carried out—starting with the modeling of the pump and hydraulic circuit, including pump parameterization and hydraulic characteristics—the simulation setup is then described, and results are discussed across various case studies involving different control methods.

These case studies include scenarios where the system is powered by a DC voltage source, as well as more realistic conditions using a PV source, with and without MPPT. Simulations also account for variable weather conditions, including fluctuating irradiance and temperature, to evaluate the system’s robustness and dynamic response under real-world operating conditions.

Special attention is given to the performance of the proposed inverter when combined with DTC-SVM hybrid method, V/f control, and Direct Torque Control (DTC) strategies. Each control approach is analyzed in terms of input/output characteristics, power quality, and overall system efficiency. Results are interpreted both quantitatively and qualitatively, including detailed power studies and general behavioral observations.

The chapter concludes with a comparative analysis of the different control methods applied to the proposed switched capacitor inverter, providing insights into their relative performance and suitability for PV water pumping applications.

3.1 Control Methods

To evaluate the performance of the system under different control strategies, three distinct methods were applied to drive the asynchronous motor. Each method offers different advantages in terms of implementation complexity, dynamic response, and robustness to source and load variations. The selected control strategies were tested under identical operating conditions to allow fair comparison and assess their influence on the overall system behavior.

A. V/f Control Method

The Voltage/Frequency (V/f) control, also referred to as *scalar control*, is among the most commonly used techniques for controlling induction motors (IMs), particularly in systems where dynamic performance is not a primary concern. This method relies on maintaining a constant ratio between the stator voltage V and the supply frequency f , thereby ensuring that the magnetic flux within the motor remains constant.

Such an approach is especially well-suited for applications involving pumps, fans, and compressors—scenarios where the load torque increases with speed and rapid torque changes are not necessary. Its simplicity, low implementation cost, and effectiveness in steady-state operation make it an attractive choice for photovoltaic (PV)-powered systems.

Theoretical Background

The V/f control method operates under the assumption of constant stator flux ϕ_s . To achieve this, it is essential to maintain a constant voltage-to-frequency ratio $\frac{V_s}{f_s}$. Starting from the stator voltage equations in the rotating d - q reference frame:

$$\begin{aligned} V_d &= R_s i_d - w_s \phi_q \\ V_q &= R_s i_q + w_s \phi_d \end{aligned} \tag{3.1}$$

Neglecting the stator resistance R_s at moderate speeds, and combining the equations into complex form:

$$\vec{V}_s \approx j w_s \vec{\phi}_s \tag{3.2}$$

Neglecting the stator resistance R_s at moderate speeds, and combining the equations into complex form:

$$\vec{V}_s \approx j w_s \vec{\phi}_s$$

Taking the magnitude gives:

$$V_s \approx w_s \phi_s \Rightarrow \frac{V_s}{f_s} \approx \phi_s = \text{constant}$$

Maintaining $\frac{V}{f} = \text{const}$ ensures a constant air-gap flux and avoids magnetic saturation or under-excitation, preserving torque capability and efficiency.

Departing from this ratio results in performance degradation:

- Increasing f without adjusting V weakens the flux, reducing torque.
- Increasing V without increasing f may saturate the core, causing losses and overheating.

Typically, voltage and frequency are scaled proportionally up to a base frequency (e.g., 50 Hz). Beyond this, voltage remains constant due to inverter limits, leading to field weakening and reduced torque.

Implementation in Simulation

In our system, a closed-loop implementation of the V/f control was used. Figure ?? shows the block diagram of the control strategy.

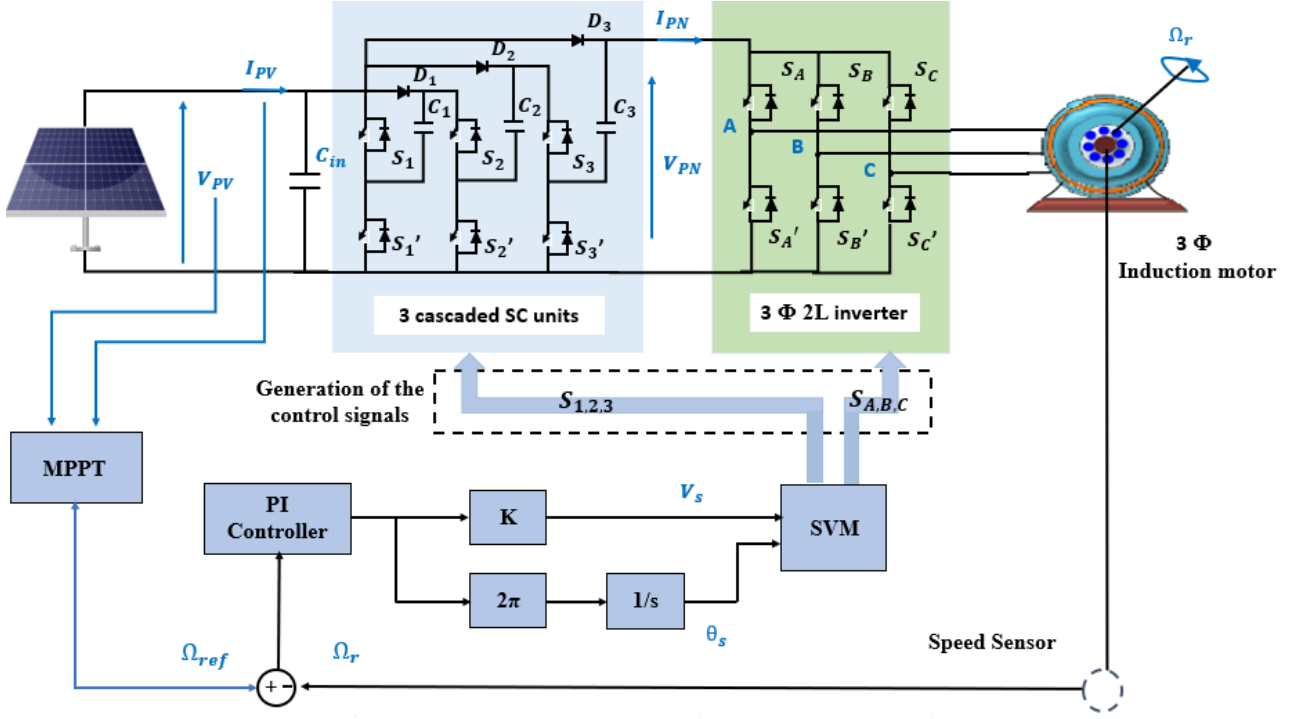


Figure 3.1: Closed-loop implementation of the V/f control strategy

The control loop operates as follows:

- A Proportional-Integral (PI) controller processes the error between the reference speed ω_{ref} and the actual rotor speed ω_r , generating a frequency reference.
- This frequency is integrated to obtain the phase angle for generating sinusoidal references.
- The stator voltage magnitude is calculated using a constant gain (e.g., $\frac{220}{50}$) to maintain a constant V/f ratio.
- Space Vector Modulation technique is used to synthesize the three-phase voltages applied to the inverter.

This closed-loop setup improves speed regulation and reduces sensitivity to load variations, offering a more stable alternative to open-loop scalar control.

B. DTC Control Method

Direct Torque Control (DTC), introduced independently by I. Takahashi and T. Noguchi and by Depenbrock in 1985, was proposed as an alternative to vector control, offering a non-linear control strategy that eliminates the need for vector transformations and decoupling. In this method, the control variables—namely the stator flux and the electromagnetic torque—are computed solely from stator-related quantities, without requiring a mechanical position sensor.

The principle of DTC control is the direct regulation of the torque of the machine, by the application of the different voltage vectors of the inverter, which determines its state. A three-phase voltage source inverter can generate eight basic voltage vectors, including two zero vectors. These vectors are selected from a switching table based on the position of the stator flux vector

as well as the errors in flux and torque, which are typically controlled by hysteresis comparators to maintain these quantities within their respective hysteresis bands.

The output of these regulators then determines the optimal voltage vector to be applied at each switching time. However, the use of hysteresis comparators assumes a variable switching frequency in the converter, requiring a very small calculation step. [59]

Stator flux control

Direct Torque Control (DTC) is a control method based on the orientation of the stator flux. Based on the induction machine model expressed in a stator reference frame and the stator voltage equation, the stator flux is estimated using the following expression :

$$\varphi_s(t) = \int_0^t (V_s - R_s I_s) dt + \varphi_{s0} \quad (3.3)$$

In the case where a non-zero voltage vector is applied over the time interval $[0, T_e]$, the drop in stator voltage due to the resistance term $R_s I_s$ may be considered negligible compared to the applied stator voltage V_s . Under this assumption, the stator flux equation simplifies to the following form:

$$\varphi_s(t) = \varphi_{s0} + V_s T_e \quad (3.4)$$

Where: φ_{s0} is the initial flux (flux vector at $t = 0$).

This expression shows that the end of the stator flux vector moves along a straight line whose direction is determined by the applied voltage vector. Thus, the stator flux vector undergoes a displacement proportional to $V_s T_e$. Consequently, the application of an appropriate voltage vector can constrain the flux vector to remain within a circular path. Therefore, the stator flux can be effectively controlled through the applied voltage vector.

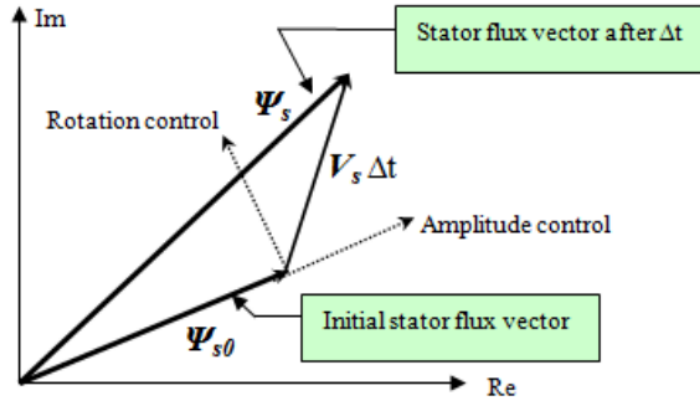


Figure 3.2: Evolution of the stator flux in the (α, β) plane

Figure 2.12.a illustrates an example of the evolution of the end of the stator flux vector under the influence of the selected voltage vector. As shown in Figure 3.2, the radial component of the voltage vector influences the amplitude of the stator flux, while the tangential component affects its angular position.

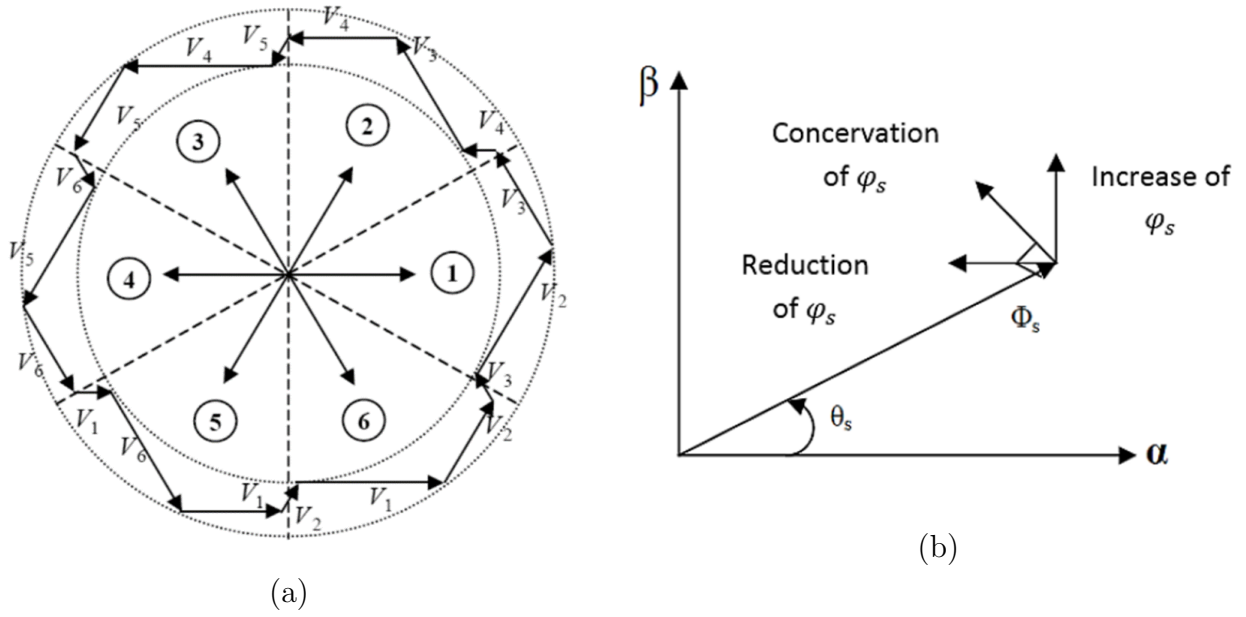


Figure 3.3: (a) Stator flux behavior for different voltage vectors V_i (b) Evolution of the stator flux vector

By selecting an appropriate sequence of voltage vectors over successive time intervals of duration T_e , it is possible to constrain the end of the stator flux vector to follow a desired trajectory. To operate with an approximately constant stator flux magnitude ϕ_s , the end of the flux vector should ideally trace a near-circular path. This condition can only be satisfied if the control period T_e (sampling interval) is significantly shorter than the rotation period of the flux vector.

Flux hysteresis comparator

A two-level hysteresis comparator is employed for flux regulation. Its objective is to maintain the tip of the stator flux vector within a circular band, as illustrated in Figure 3.3.a. The input to the comparator is the flux amplitude error. The output of the controller, represented by a Boolean variable S_φ , directly indicates whether the flux amplitude should be increased [$S_\varphi = 1$] or decreased [$S_\varphi = 0$] to maintain it within the desired bounds.

The comparator operates according to equation (3.14). This type of controller enables good dynamic performance of the flux.

$$S_\varphi = \begin{cases} 1 & \text{if } \Delta\varphi_s > h_{\varphi_s} \\ 0 & \text{if } 0 \leq |\Delta\varphi_s| \leq h_{\varphi_s} \text{ and } \frac{d\Delta\varphi_s}{dt} > 0 \\ 1 & \text{if } 0 \leq |\Delta\varphi_s| \leq h_{\varphi_s} \text{ and } \frac{d\Delta\varphi_s}{dt} < 0 \\ 0 & \text{if } \Delta\varphi_s < -h_{\varphi_s} \end{cases} \quad (3.5)$$

Where $\Delta\varphi_s = |\varphi_s|^* - |\varphi_s|$ is the flux error and, h_{φ_s} is the hysteresis band.

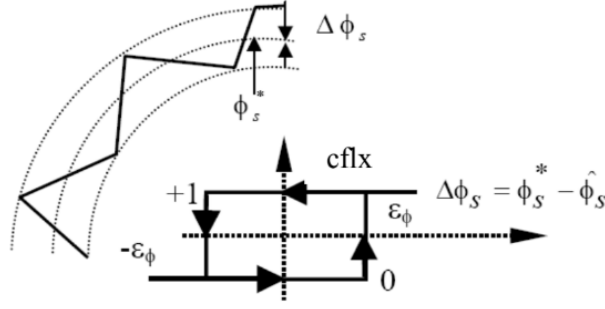


Figure 3.4: Hysteresis comparator used to control the stator flux

Electromagnetic torque control

The electromagnetic torque produced in an electric machine is proportional to the vector product of the stator and rotor magnetic flux vectors. The electromagnetic torque of the induction machine can be expressed in the following form:

$$C_{em} = p \cdot \frac{M}{\sigma L_s \cdot L_r} \|\varphi_s\| \cdot \|\varphi_r\| \cdot \sin(\theta_{sr}) \quad (3.16)$$

Where: θ_{sr} is the angle between the stator and rotor flux vectors.

The rotor flux can be expressed as a function of the stator flux as follows:

$$\varphi_r = \frac{M}{L_s} \cdot \frac{\varphi_s}{1 + j\sigma T_r} \quad (3.6)$$

where σT_r determines the speed of variation of the angle θ_{sr} between the two fluxes. Therefore, if we can control the stator flux and its position, we can control the rotor flux and θ_{sr} . This can be done when condition $T_e \ll \sigma T_r$ is met. So, the control of the torque depends directly on the control of the rotation of the stator flux vector.

Torque hysteresis comparator

The torque controller is designed to maintain the torque within the limits $|T_{e_{ref}} - T_e| < \Delta T_e$, where $C_{e_{ref}}$ is the reference torque and ΔT_e is the hysteresis band of the controller. However, unlike flux control, the torque can be either positive or negative depending on the direction of machine rotation.

In the design of the torque controller, two types of hysteresis comparators may be considered to achieve the desired torque dynamics:

- **A two-level hysteresis controller** : Controls the torque in only one direction of motor rotation.
- **A three-level hysteresis controller** : Enables motor control in both rotational directions, supporting both positive and negative torque.

In the case of switched capacitor inverter a nine-level hysteresis comparator is utilized for torque correction to fix the ripple, using the torque hysteresis comparator band.

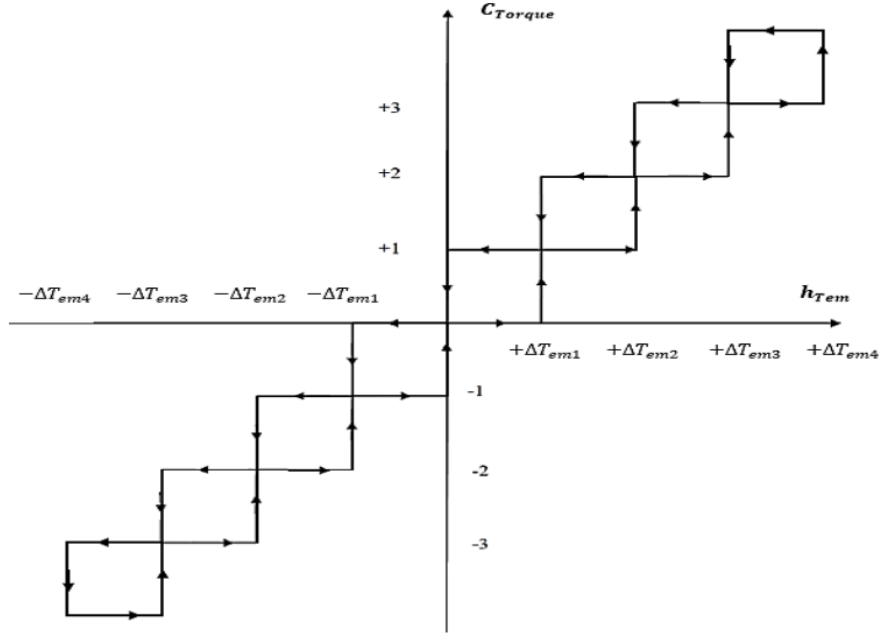


Figure 3.5: 9-level torque controller

Estimation of stator flux and electromagnetic torque

- Estimation of the Stator Flux

The estimation of the stator flux vector is carried out using the voltage and current vectors. The expression for the flux is given by :

$$\varphi_s = \int_0^t (V_s - R_s I_s) dt \quad (3.7)$$

The stator flux vector is calculated from its two-phase components in the (α, β) reference frame, as follows:

$$\varphi_s = \varphi_{s\alpha} + j\varphi_{s\beta} \quad (3.8)$$

With :

$$\begin{cases} \varphi_{s\alpha} = \int_0^t (V_{s\alpha} - R_s I_{s\alpha}) dt \\ \varphi_{s\beta} = \int_0^t (V_{s\beta} - R_s I_{s\beta}) dt \end{cases} \quad (3.9)$$

To calculate the components $(I_{s\alpha}, I_{s\beta})$ and $(V_{s\alpha}, V_{s\beta})$ of the stator current and voltage vectors, the Concordia transformation is used :

$$\begin{cases} I_{s\alpha} = \sqrt{\frac{2}{3}} \left(I_{sa} - \frac{1}{2}(I_{sb} + I_{sc}) \right) \\ I_{s\beta} = \frac{1}{\sqrt{2}}(I_{sb} - I_{sc}) \end{cases} \quad (3.10)$$

$$\begin{cases} V_{s\alpha} = \sqrt{\frac{2}{3}} \left(V_{sa} - \frac{1}{2}(V_{sb} + V_{sc}) \right) \\ V_{s\beta} = \frac{1}{\sqrt{2}}(V_{sb} - V_{sc}) \end{cases} \quad (3.11)$$

The magnitude and The position of the stator flux are given by:

$$\begin{cases} |\vec{\varphi}_s| = \sqrt{\varphi_{s\alpha}^2 + \varphi_{s\beta}^2} \\ \theta_s = \tan^{-1} \left(\frac{\varphi_{s\beta}}{\varphi_{s\alpha}} \right) \end{cases} \quad (3.12)$$

- Estimation of the Electromagnetic Torque

The electromagnetic torque can be estimated from the stator currents $I_{s\alpha}$ and $I_{s\beta}$, and the estimated fluxes $\phi_{s\alpha}$ and $\phi_{s\beta}$, as given by the following relation:

$$T_e = p (\phi_{s\alpha} I_{s\beta} - \phi_{s\beta} I_{s\alpha}) \quad (3.13)$$

Selection of Vectors

The selection of $\mathbf{V}_s$ depends not only on the desired variation in the flux magnitude but also on the required evolution of its rotational speed and, consequently, the electromagnetic torque. The space in which the stator flux vector ϕ_s evolves is typically divided into six symmetrical sectors in the stationary (stator) reference frame, aligned with the directions of the non-zero voltage vectors.

When the stator flux vector ϕ_s lies within a sector numbered $N = i$, the control of both flux and torque can be achieved by selecting one of the eight available voltage vectors.

In general:

- To increase the magnitude of the stator flux, vectors V_i , V_{i+1} , or V_{i-1} can be applied.
- To decrease the magnitude of the stator flux, vectors V_{i+2} , V_{i+3} , or V_{i-2} can be used.
- To increase the torque, vectors V_{i+1} or V_{i+2} are suitable.
- To decrease the torque, vectors V_{i-1} or V_{i-2} can be applied.

The application of a zero voltage vector holds the stator flux vector stationary, causing the torque to decrease. By fixing the stator flux vector, the rotor flux vector tends to align with it, thereby reducing the angle γ , which in turn leads to a reduction in the electromagnetic torque.

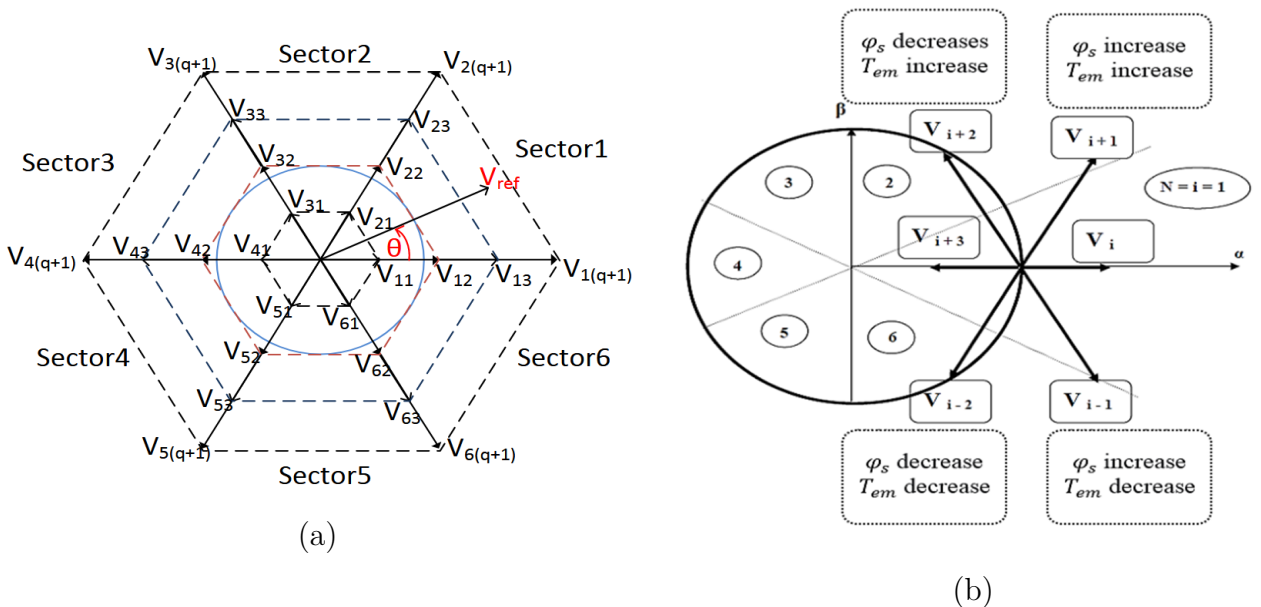


Figure 3.6: (a) The space vector diagram (b) The principle of voltage vector selection

Switching table

To achieve direct control of the electromagnetic torque of an asynchronous machine powered by the proposed switched capacitor inverter, it is necessary to develop a switching table. This table's construction (Table III.1) is based on selecting the appropriate stator voltage vector to increase or decrease both the stator flux magnitude and the electromagnetic torque value.

$\mathcal{C}_{\varphi_s}$	$C_{T_{em}}$	Stator flux vector sector					
		1	2	3	4	5	6
1	4	V_{24}	V_{34}	V_{44}	V_{54}	V_{64}	V_{14}
	3	V_{23}	V_{33}	V_{43}	V_{53}	V_{63}	V_{13}
	2	V_{22}	V_{32}	V_{42}	V_{52}	V_{62}	V_{12}
	1	V_{21}	V_{31}	V_{41}	V_{51}	V_{61}	V_{11}
	0	V_{71}	V_{01}	V_{71}	V_{01}	V_{71}	V_{01}
	-1	V_{61}	V_{11}	V_{21}	V_{31}	V_{41}	V_{51}
	-2	V_{62}	V_{12}	V_{22}	V_{32}	V_{42}	V_{52}
	-3	V_{63}	V_{13}	V_{23}	V_{33}	V_{43}	V_{53}
	-4	V_{64}	V_{14}	V_{24}	V_{34}	V_{44}	V_{54}
-1	4	V_{34}	V_{44}	V_{54}	V_{64}	V_{14}	V_{24}
	3	V_{33}	V_{43}	V_{53}	V_{63}	V_{13}	V_{23}
	2	V_{32}	V_{42}	V_{12}	V_{62}	V_{22}	V_{12}
	1	V_{31}	V_{41}	V_{11}	V_{61}	V_{71}	V_{21}
	0	V_{01}	V_{71}	V_{01}	V_{71}	V_{01}	V_{71}
	-1	V_{51}	V_{61}	V_{11}	V_{21}	V_{31}	V_{41}
	-2	V_{52}	V_{62}	V_{12}	V_{22}	V_{32}	V_{42}
	-3	V_{53}	V_{63}	V_{13}	V_{23}	V_{33}	V_{43}
	-4	V_{54}	V_{64}	V_{14}	V_{24}	V_{34}	V_{44}

Table 3.1: Switching table for stator voltage vector selection based on $\mathcal{C}_{\varphi_s}$ and $C_{T_{em}}$.

Control scheme

The general structure of the DTC control scheme used for the switched capacitor inverter is presented in the following figure :

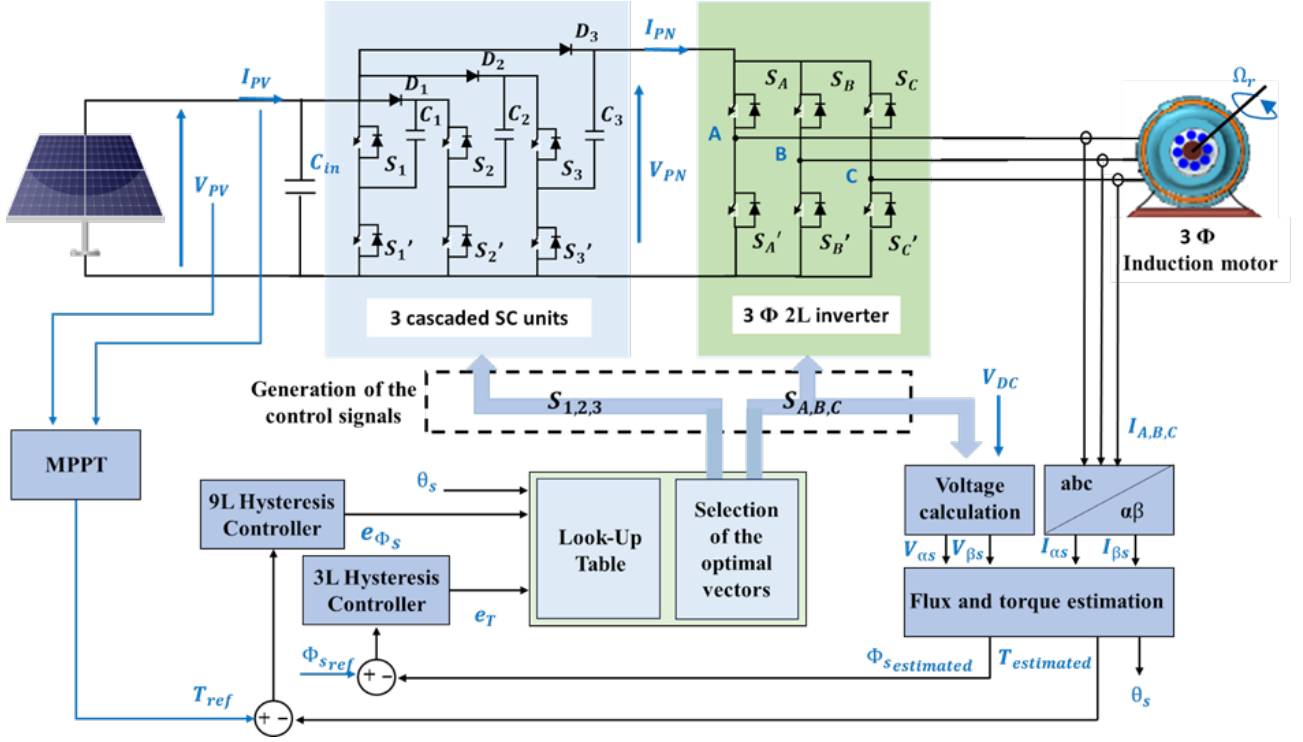


Figure 3.7: Closed-loop implementation of the DTC control strategy

C. DTC-SVM Control Method

Direct Torque Control with Space Vector Modulation (DTC-SVM) was introduced to address the limitations of conventional DTC, particularly its variable switching frequency and high torque ripple. Unlike classical DTC, which directly computes and generates the instantaneous control voltage vectors (control signals), DTC-SVM determines an appropriate reference voltage vector based on averaged values that ensures accurate torque and flux regulation. This reference voltage is synthesized using Space Vector Modulation (SVM), resulting in a fixed switching frequency and improved control performance.

The specific implementation of DTC-SVM can vary depending on the specific flux and torque control algorithm employed. Consequently, several structural variations of DTC-SVM exist. In this work, we focus on a control architecture that utilizes two Proportional-Integral (PI) controllers to regulate the flux and torque loops within the stator flux reference frame.

The proposed approach preserves the core concept of the conventional DTC method, namely the decoupled control of the stator flux and electromagnetic torque. To achieve this, stator flux orientation is applied, with a dedicated PI controller integrated for each control variable. These controllers generate the necessary reference voltages, which are then fed into the Space Vector Modulation (SVM) block. [59]

This control architecture is composed of three main components:

- A flux and torque estimator, used to determine the actual values of stator flux and electromagnetic torque;
- Two PI controllers for regulating torque and flux, along with a PI speed controller responsible for calculating the torque reference;

- The SVM block, which generates the appropriate space voltage vector and provides the corresponding control pulses for the Switched Capacitor Inverter (SCI).

Machine Modeling for Control purposes

The DTC-SVM control strategy relies on the decoupled regulation of electromagnetic torque and stator flux using Proportional-Integral (PI) controllers. To facilitate this decoupling, the control is implemented in the stator flux-oriented reference frame (x, y). In this rotating reference frame, the stator flux vector is aligned along the x-axis, effectively simplifying the control structure. This orientation allows for independent control of torque and flux components, as illustrated in the corresponding figure :

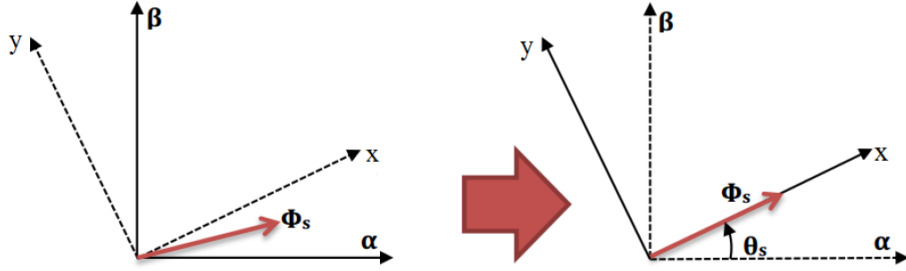


Figure 3.8: Vector diagram of the stator flux orientation control strategy

The complete set of motor model equations can be written in the stator flux coordinate system $x - y$. This coordinate system $x - y$ rotates with the stator flux angular speed $w_K = w_{ss}$. This angular speed is defined as follows:

$$w_{ss} = \frac{d\theta_{\phi_s}}{dt} \quad (4.2)$$

where θ_{ϕ_s} is the angle of the stator flux vector.

The space vectors in these coordinates are defined as follows:

$$\text{Output voltage vector: } \mathbf{U}_{ss} = U_{sx} + jU_{sy} \quad (4.3)$$

$$\text{Stator current vector: } \mathbf{I}_{ss} = I_{sx} + jI_{sy} \quad (4.4)$$

$$\text{Stator flux vector: } \boldsymbol{\phi}_s = \phi_{sx} \quad (4.5)$$

$$\text{Rotor current vector: } \mathbf{I}_{rs} = I_{rx} + jI_{ry} \quad (4.6)$$

$$\text{Rotor flux vector: } \boldsymbol{\phi}_{rs} = \phi_{rx} + j\phi_{ry} \quad (4.7)$$

The asynchronous machine equations in this frame can be written as:

$$U_{sx} = R_s I_{sx} + \frac{d\phi_s}{dt} \quad (4.8)$$

$$U_{sy} = R_s I_{sy} + \Omega_{ss} \phi_s \quad (4.9)$$

$$0 = R_r I_{rx} + \frac{d\phi_{rx}}{dt} + \phi_{ry}(p\Omega_m - w_{ss}) \quad (4.10)$$

$$0 = R_r I_{ry} + \frac{d\phi_{ry}}{dt} - \phi_{rx}(w_{ss} + p\Omega_m) \quad (4.11)$$

Flux-current relationships:

$$\phi_s = L_s I_{sx} + L_M I_{rx} \quad (4.12)$$

$$0 = L_s I_{sy} + L_M I_{ry} \quad (4.13)$$

$$\phi_{rx} = L_r I_{rx} + L_M I_{sx} \quad (4.14)$$

$$\phi_{ry} = L_r I_{ry} + L_M I_{sy} \quad (4.15)$$

Mechanical equation:

$$\frac{dw_m}{dt} = \frac{1}{J} (C_{em} - C_r - C_f) \quad (4.16)$$

So we will have:

$$\phi_{sx} = \phi_s \quad \phi_{sy} = 0 \quad (2.9)$$

Then the machine model in this reference frame becomes:

$$\begin{cases} V_{sx} = R_s I_{sx} + \frac{d\phi_s}{dt} \\ V_{sy} = R_s I_{sy} + s \phi_s \\ \Gamma_e = p \phi_s I_{sy} \end{cases} \quad (2.10)$$

From the model obtained above, we can deduce the flux and torque expressions that we will use to synthesize our control law [21]:

$$\begin{cases} \frac{d\phi_s}{dt} = V_{sx} - R_s I_{sx} \\ \Gamma_e = \frac{3}{2} \frac{p}{R_s} \phi_s (V_{sy} - s \phi_s) \end{cases} \quad (2.11)$$

The simple functional diagram of the asynchronous machine based on equation (2.11) is represented in the following Figure 2.2:

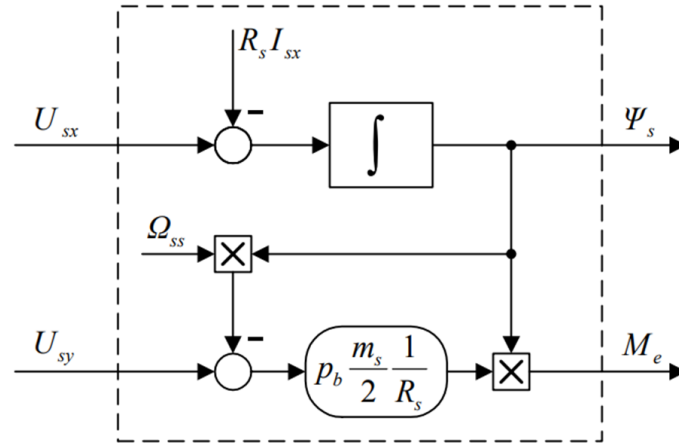


Figure 3.9: Simplified (rotor equation omitted) induction motor block diagram in the stator flux-oriented coordinates $x - y$

Considering a simple model of IM (Fig. 4.7), Fig. 4.8 shows the flux and torque control loops for the method shown in Fig. 4.5. In Fig. 4.8 the dashed line represents the IM model.

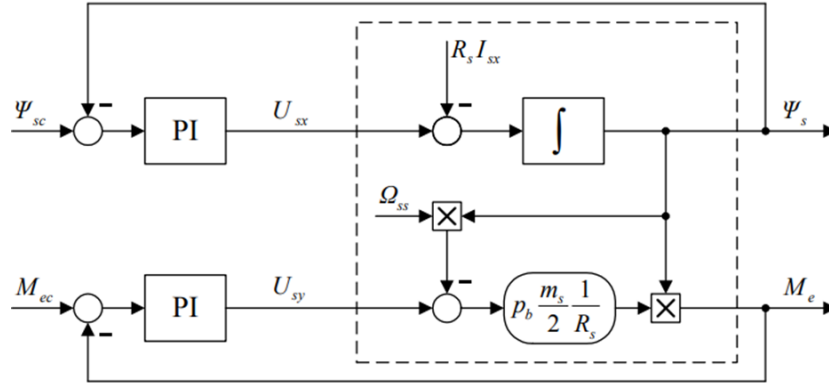


Figure 3.10: Control loops with two PI controllers and simplified IM mode

The transformation from the X/Y reference frame to the α/β reference frame is performed as follows:

$$\begin{cases} U_\alpha = \cos(\theta_{\phi_s})U_{sx} - \sin(\theta_{\phi_s})U_{sy} \\ U_\beta = \sin(\theta_{\phi_s})U_{sx} + \cos(\theta_{\phi_s})U_{sy} \end{cases} \quad (3.14)$$

Control scheme

The structure of the PI-based DTC-SVM control scheme used for the switched capacitor inverter is presented in the following figure:

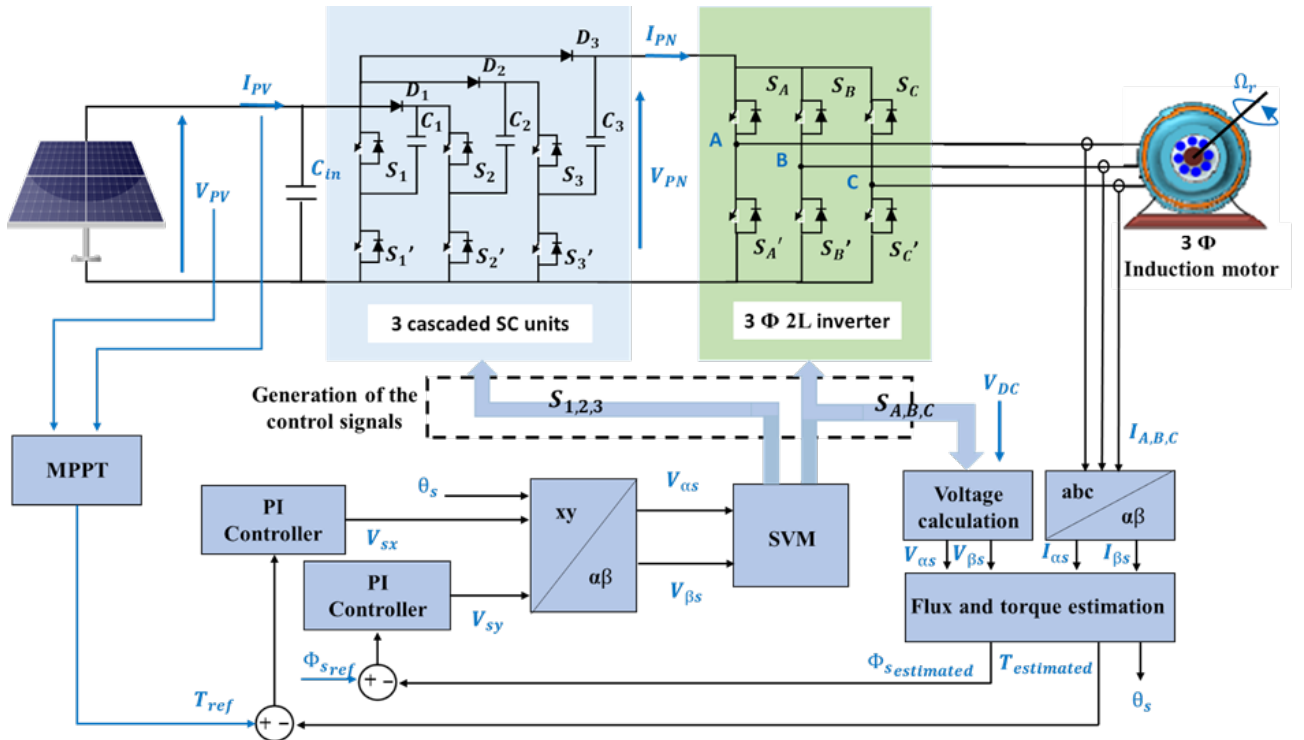


Figure 3.11: Closed-loop implementation of the DTC-SVM control strategy

3.1.1 Simulation results and discussion

This section presents the results of the simulation study conducted to evaluate the performance of the proposed switched capacitor inverter topology under various operating conditions. The analysis covers different input sources—including DC, PV without MPPT, and PV with MPPT—as well as multiple environmental scenarios involving fixed and variable irradiance and temperature.

To ensure a comprehensive assessment, each input condition was tested with the three control strategies applied to the asynchronous motor: DTC-SVM, conventional DTC, and scalar V/f control. In the case of DTC-SVM, additional emphasis is placed on the system response under a PV source without MPPT, as this scenario clearly highlights the effects of unregulated power input on system stability. This subsections detail the simulation results for each control method, providing a comparative discussion of system behavior across different operating scenarios.

3.1.1.1 DTC-SVM Control Method

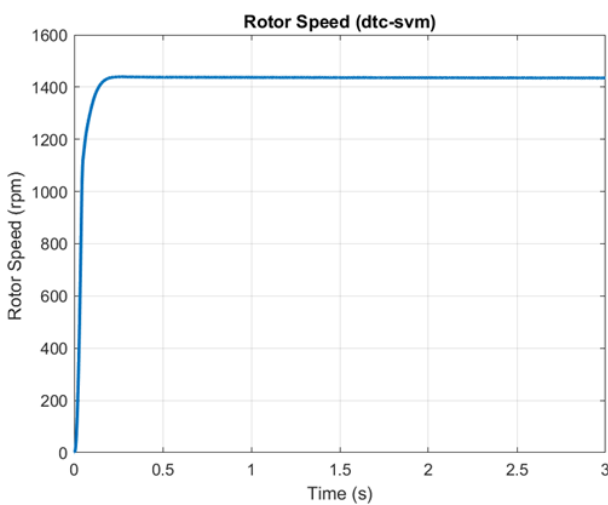
Case 1: DC voltage source:

The first case evaluates the performance of the DTC-SVM control method when the system is powered by a stable DC voltage source, providing a reference scenario under ideal supply conditions. The simulation parameters for the inverter and the asynchronous motor driving the pump are listed in Table 3.4.

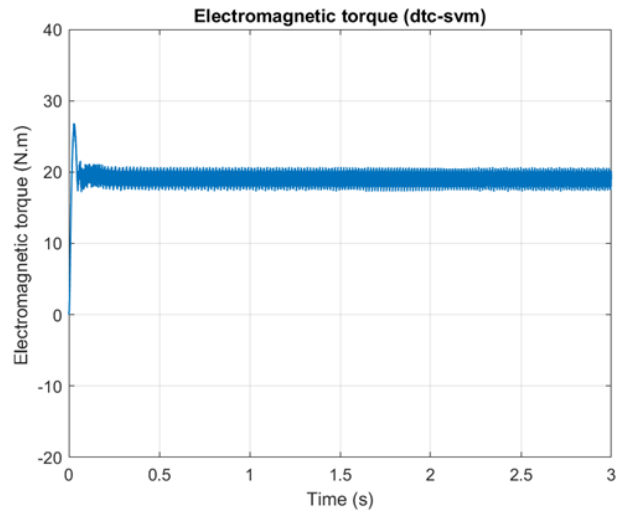
Parameter	V_{dc}	f	P_n	n_n
Value	180 V	5 kHz	4 kW	1430 rpm

Table 3.2: The parameters and values of the components in the case of a DC voltage source feeding an asynchronous motor coupled to a centrifugal pump

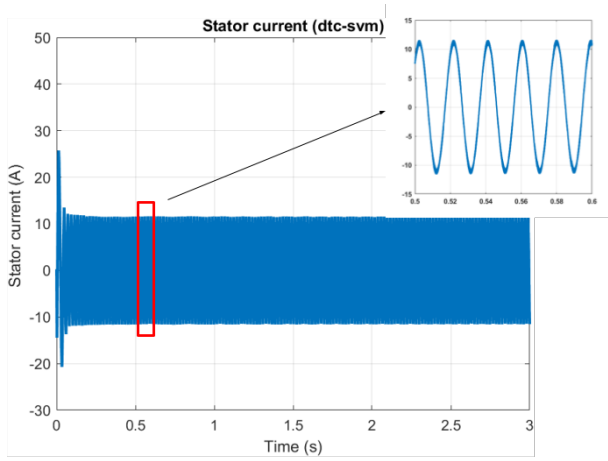
The simulation results corresponding to this configuration are presented below.



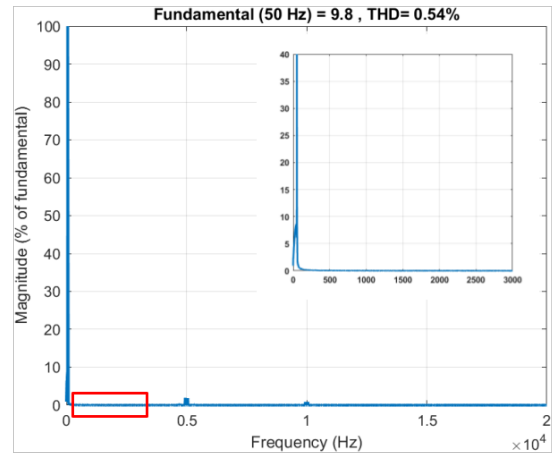
(a) Rotor speed



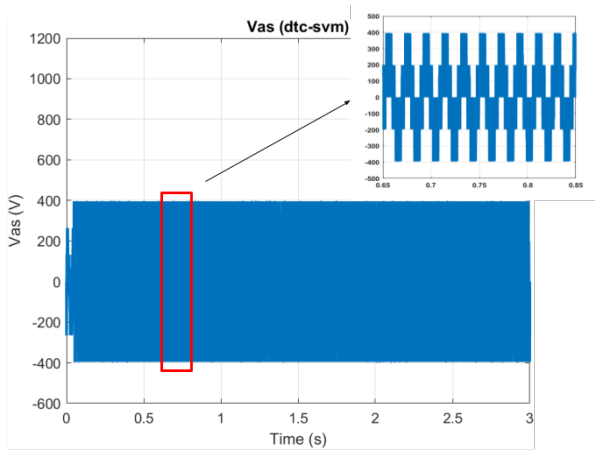
(b) Electromagnetic torque



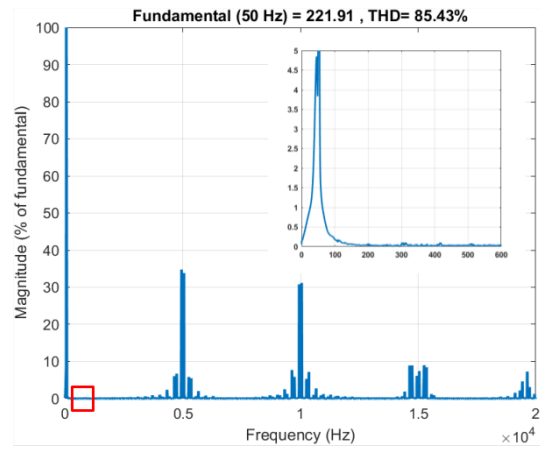
(c) Stator current



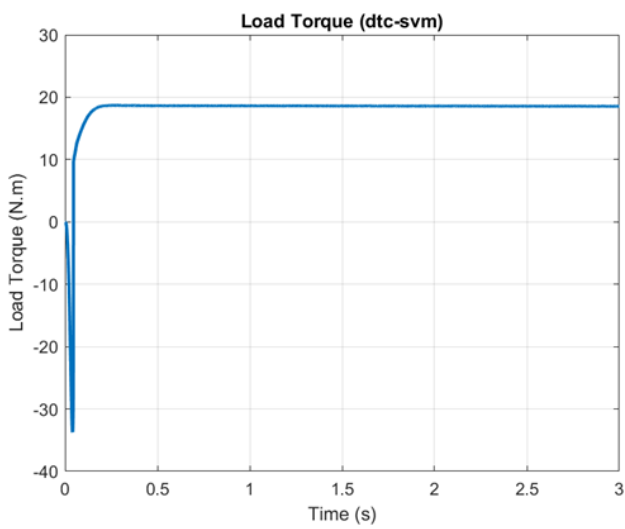
(d) The fft analysis of the output current



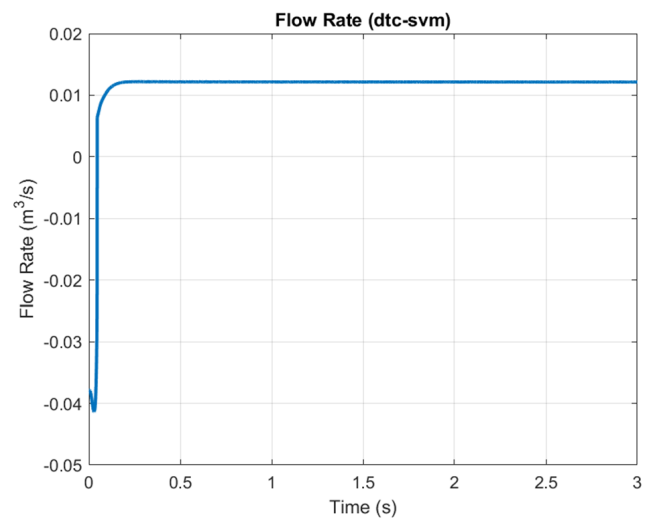
(e) Output voltage



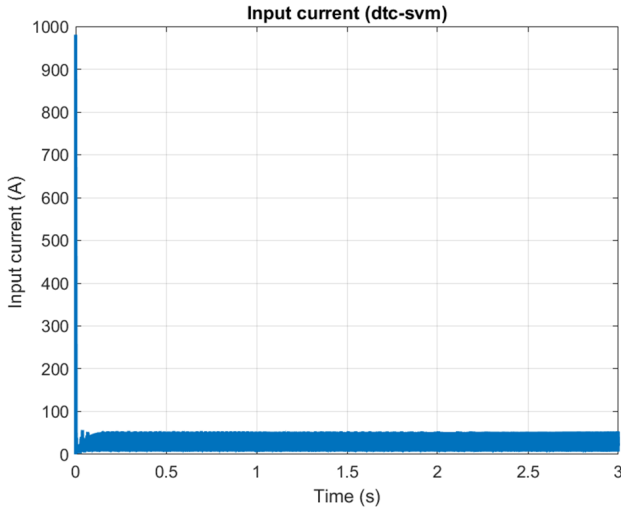
(f) The fft analysis of the output voltage



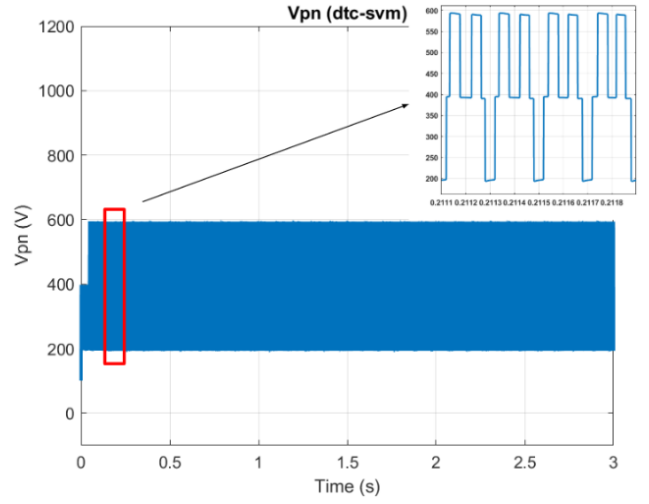
(g) Load torque



(h) Flow rate



(i) Input current



(f) DC link voltage

3.1.1.1.1 Interpretation of the results

- Figure (e) shows That the output voltage waveform of the inverter is a multilevel voltage waveform with an obtained fundamental magnitude is equal to 221.91 and it follows its reference. The difference between the fundamental and the reference is due to the voltage drop across the semiconductors and the capacitor of the SC inverter.
- When analyzing the output voltage harmonic spectrum, it is clear that there are no low frequency harmonics. The main harmonics are concentrated around the switching frequency (1 MHz) and its multiples while the low frequency harmonics are very low ($<0.5\%$ of the fundamental).
- Figure (c) shows the output current, which is clearly sinusoidal and has very few harmonic components. This justifies the low Total Harmonic Distortion (THD) value of 0.54%.
- When analyzing the output current harmonic spectrum shown in Figure (d), it is clear that the main harmonics are around the switching frequency which is equal to 1 MHz and its multiples. The low frequency harmonics are very low ($<0.2\%$ of the fundamental)

Case 2: PV Source without MPPT

The second case evaluates the performance of the DTC-SVM control strategy when the system is powered by a photovoltaic (PV) source, we simulate the proposed switched capacitor inverter supplying an asynchronous motor coupled to a pump. This test case aims to assess the system's dynamic behavior under realistic conditions, allowing direct comparison of the system's response under different power supply configurations.

The $I(V)$ and $P(V)$ characteristics represent the relationship between the current, voltage, and output power of the PV generator. They are essential for identifying the maximum power point (MPP), especially when analyzing the performance of the system under varying temperature and irradiation conditions.

The parameters of the PV generator used in the simulation are listed in the Table below:

Panel type	Number of series modules	Number of parallel strings
User-defined	5	4

Table 3.3: The parameters of the PV generator

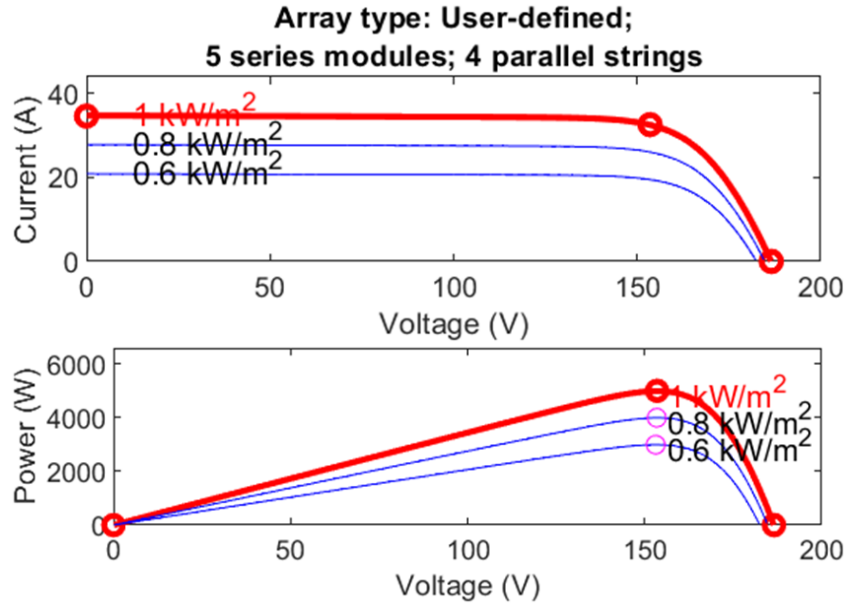


Figure 3.12: The $I(V)$ and $P(V)$ characteristics of the PV array (Effect of irradiance)

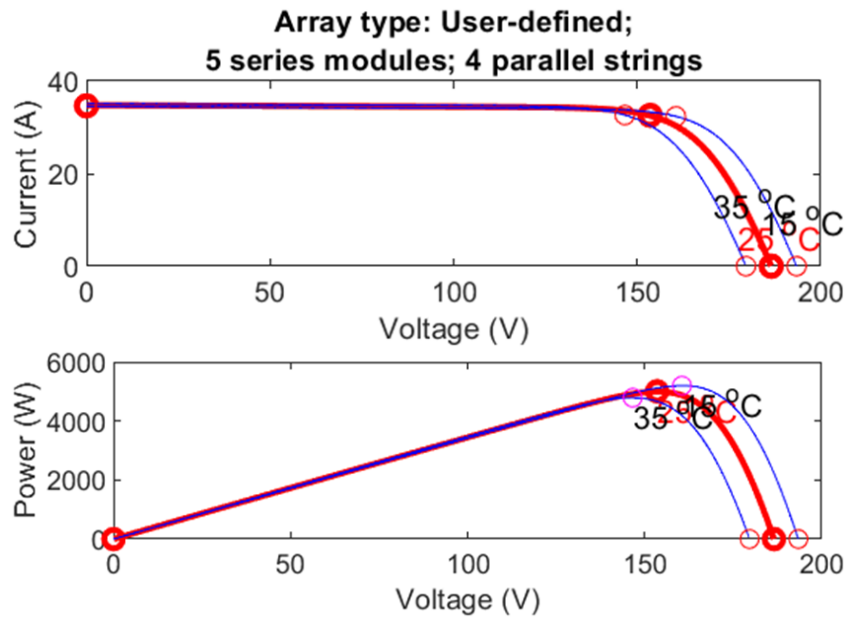
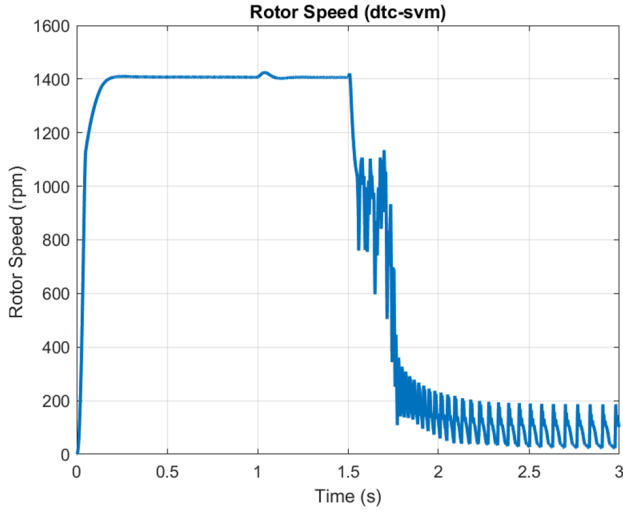


Figure 3.13: The $I(V)$ and $P(V)$ characteristics of the PV array (Effect of temperature)

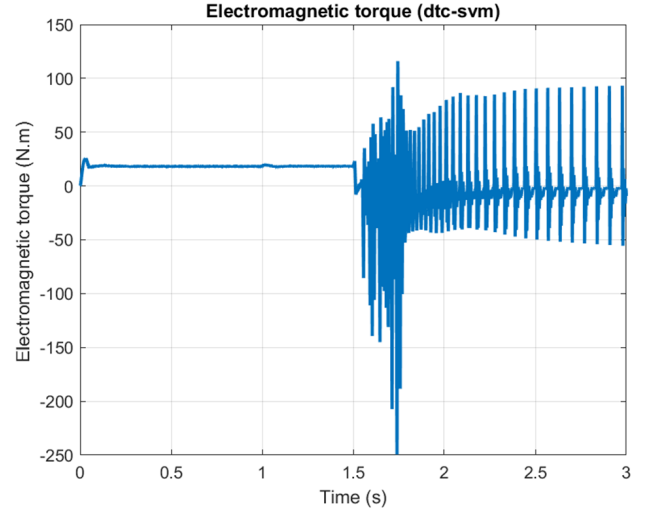
- **A/** Variable irradiance ($I=1000-800-600 \text{ kW/m}^2$), constant temperature ($T=25^\circ\text{C}$)

The output voltage of a photovoltaic (PV) module is directly proportional to the level of irradiance it receives. For a water pumping system powered by a PV source, it is important to understand how changes in irradiance affect the system's performance. While temperature also influences PV system performance, it tends to vary gradually, unlike irradiance, which can fluctuate suddenly due to cloud cover.

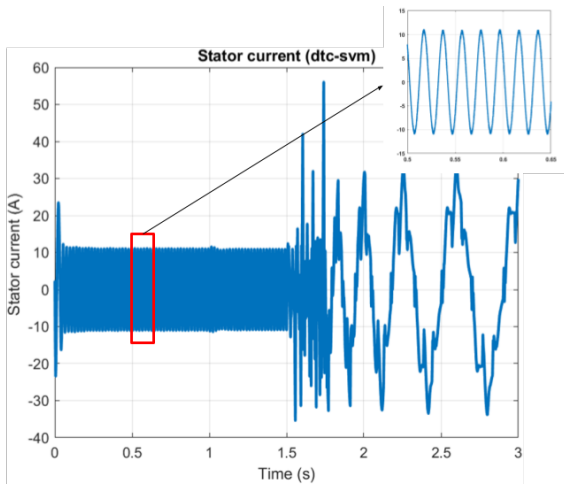
To investigate the impact of sudden changes in irradiance, a simulation was performed with an initial irradiance level of 1000 W/m^2 . After 1 second, the irradiance was reduced to 800 W/m^2 , and then to 600 W/m^2 after 1.5 seconds. The simulation results demonstrated how the system responded to these variations in irradiance.



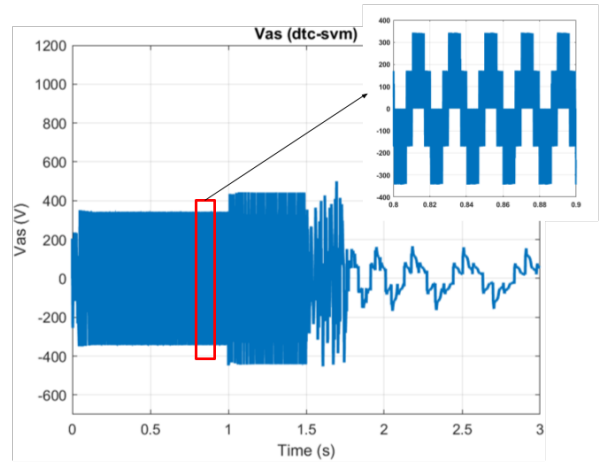
(a) Rotor speed



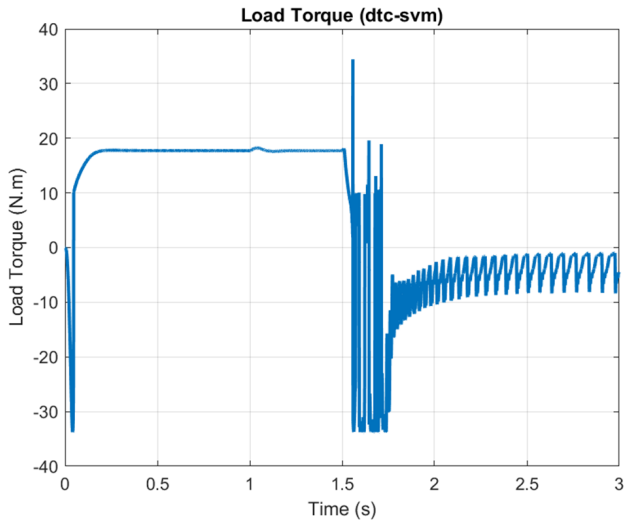
(b) Electromagnetic torque



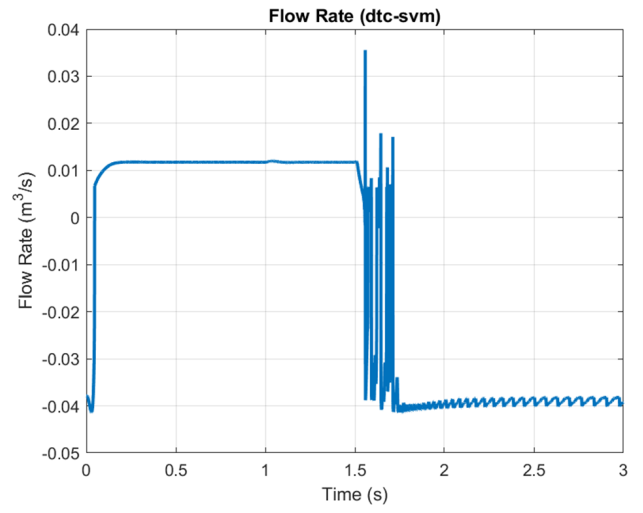
(c) Stator current



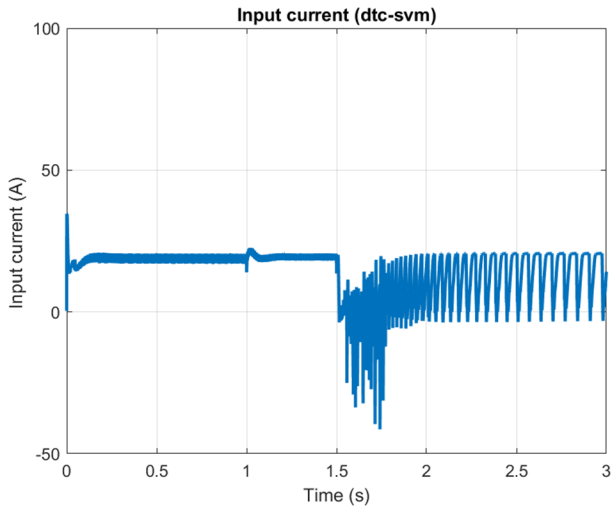
(d) Output voltage



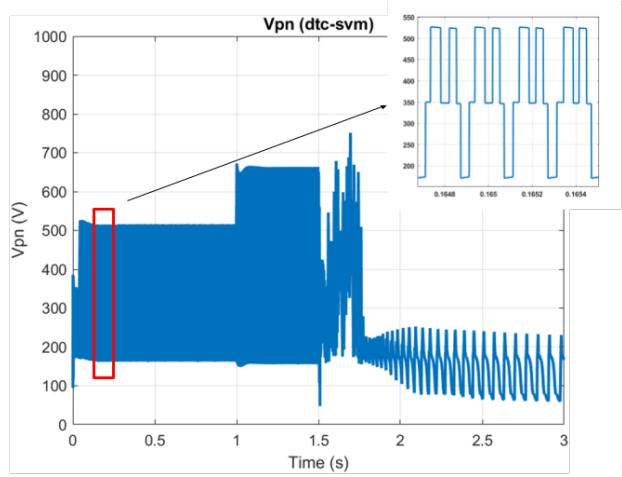
(e) Load torque



(f) Flow rate



(g) Input current I_{PV}



(h) DC link voltage

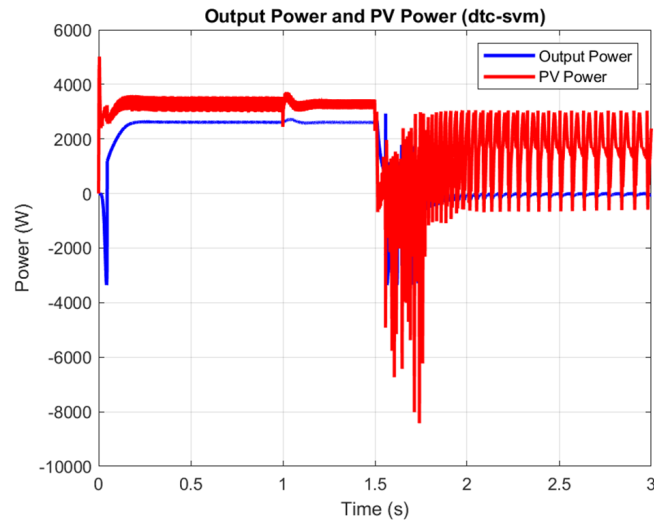


Figure 3.14: Comparison between the output power and the PV power

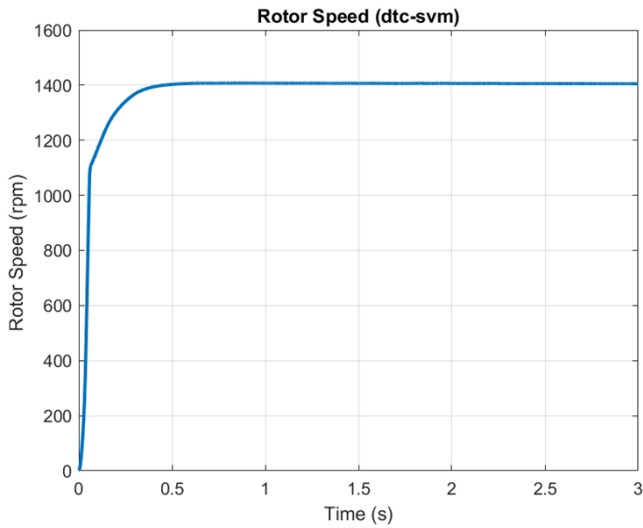
3.1.1.1.2 Interpretation of the results

- At an irradiance level of 600 W/m^2 , the photovoltaic (PV) source can no longer provide sufficient power to meet the electrical and mechanical demands of the motor-pump system. This power deficit leads to a complete destabilization of the system. The motor speed drops to zero as the available power is insufficient to sustain rotation. With a significant drop in DC-link voltage, the inverter's output voltage and current decrease sharply, leading to a loss of electromagnetic torque. The motor fails to generate the torque required to drive the pump, contributing to the stall condition.
- This operating point highlights the need for implementing a Maximum Power Point Tracking (MPPT) algorithm. MPPT ensures that, under varying irradiance levels, the PV source operates at its optimal power point. By dynamically adjusting the operating voltage of the PV module, MPPT maximizes energy extraction and stabilizes the power supplied to the system, thereby improving performance and extending operating range even during partial shading or cloud transients.

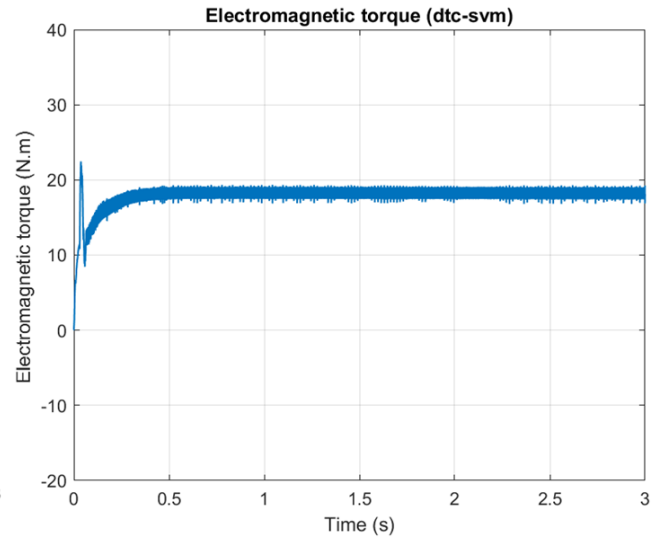
Case 3: PV Source with MPPT

The third case study examines the photovoltaic (PV) system in which the proposed switched capacitor inverter supplies an asynchronous motor coupled to a pump. The Perturb and Observe (P&O) algorithm is applied to track the maximum power point of the PV source. This test aims to evaluate the performance of the DTC-SVM control strategy and assess the system's dynamic behavior under realistic operating conditions.

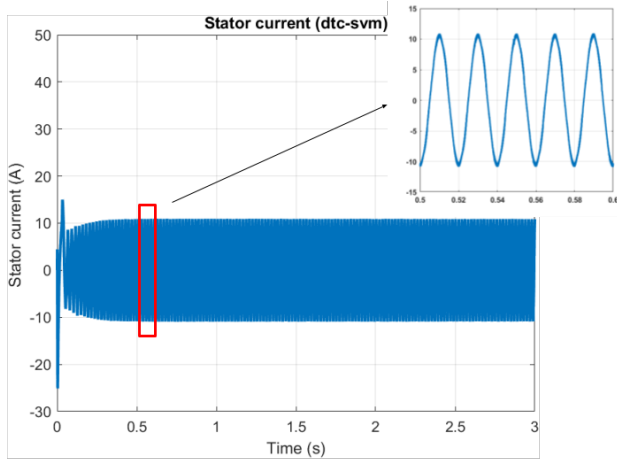
- **A/** Constant irradiance ($I=1000 \text{ kW/m}^2$) and temperature ($T=25^\circ\text{C}$)



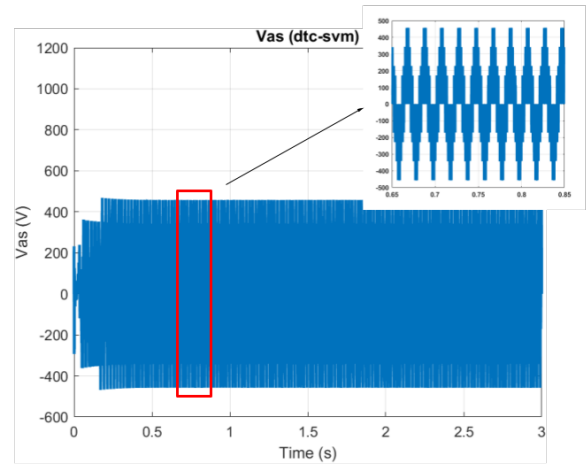
(a) Rotor speed



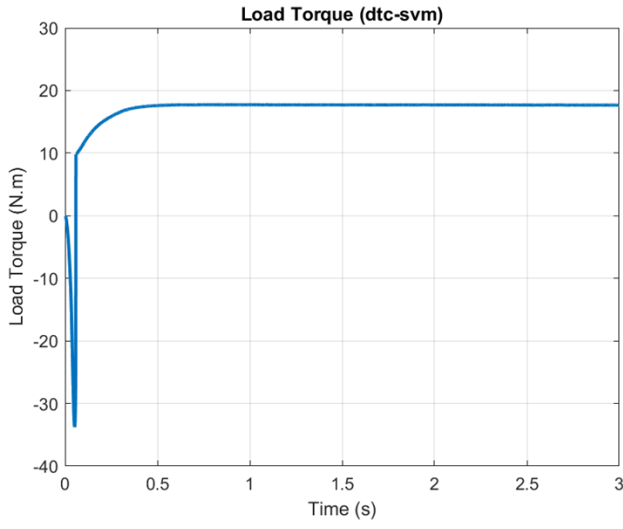
(b) Electromagnetic torque



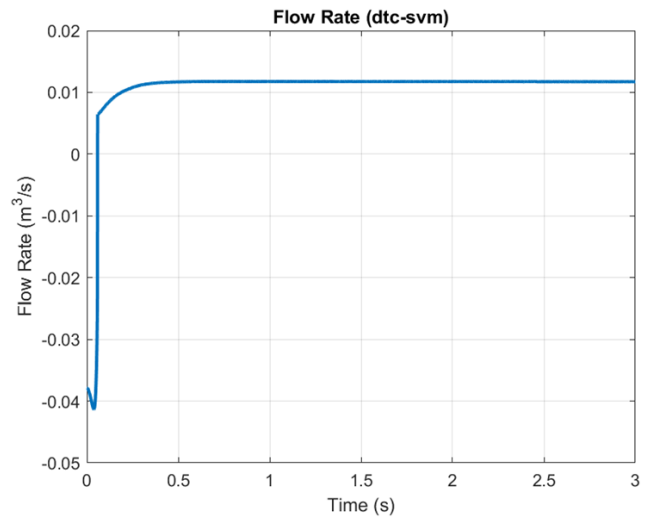
(c) Stator current



(d) Output voltage



(e) Load torque



(f) Flow rate

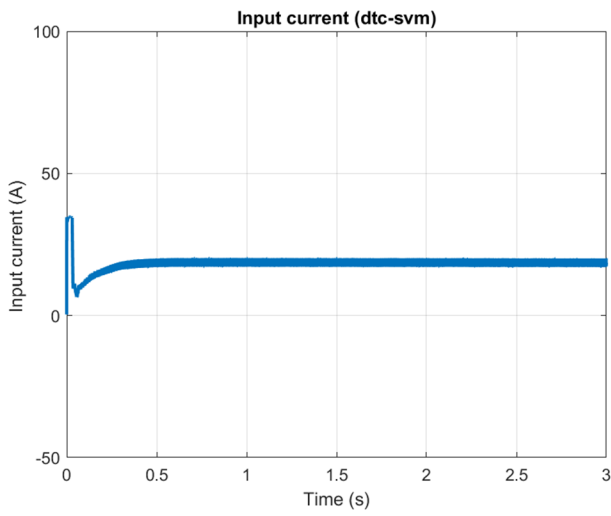
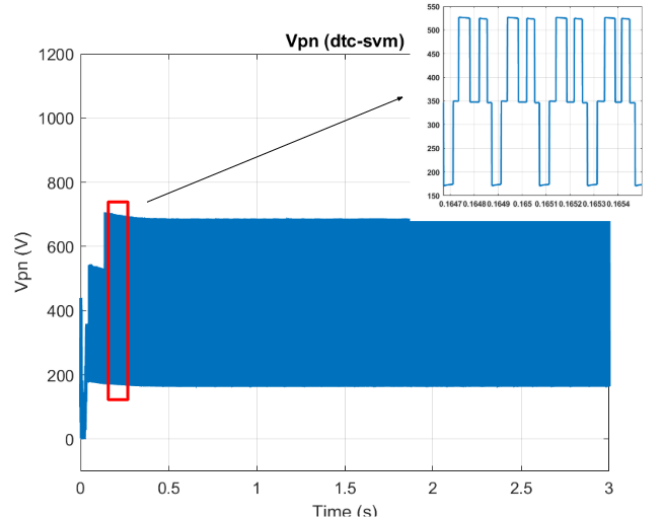


Figure 3.15: (g) Input current I_{PV}



(h) DC link voltage

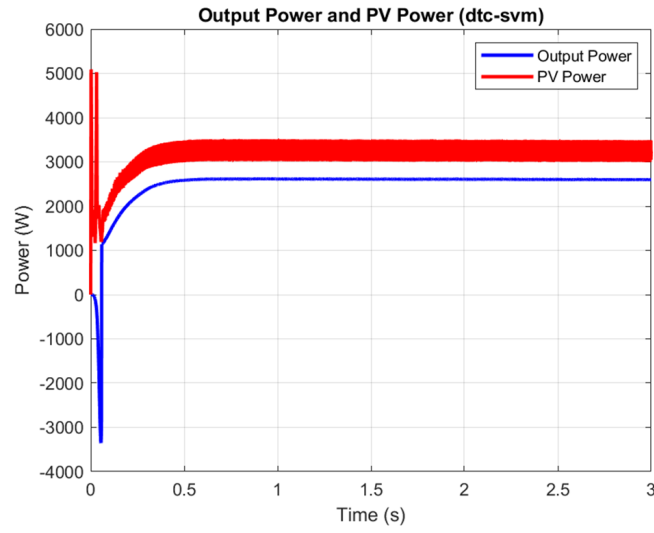
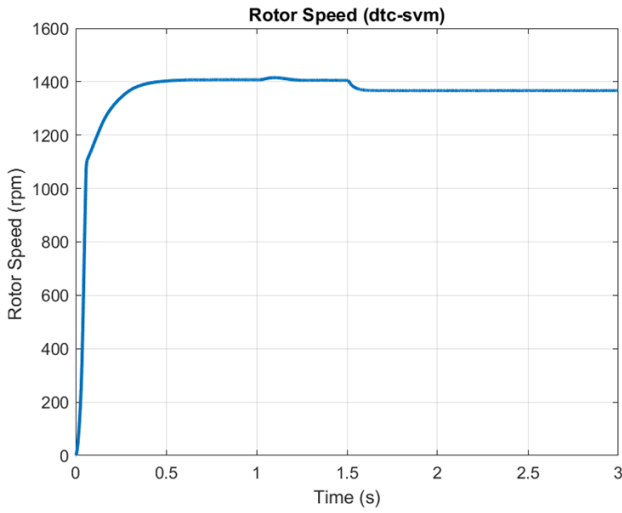
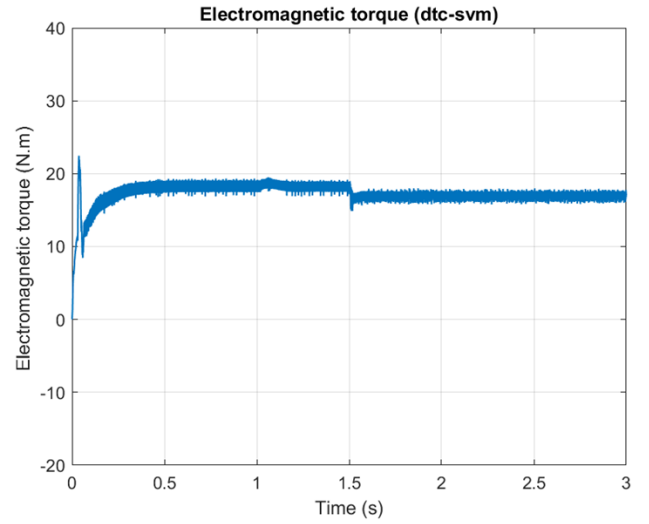


Figure 3.16: (i) Comparison between the output power and the PV power

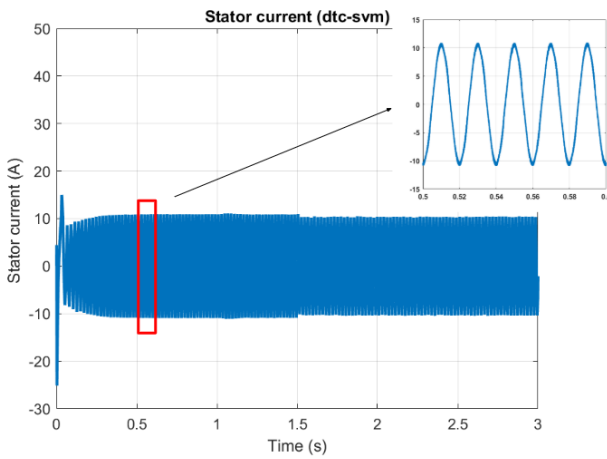
- **B/** Variable irradiance ($I=1000-800-600 \text{ kW/m}^2$), constant temperature ($T=25^\circ\text{C}$)



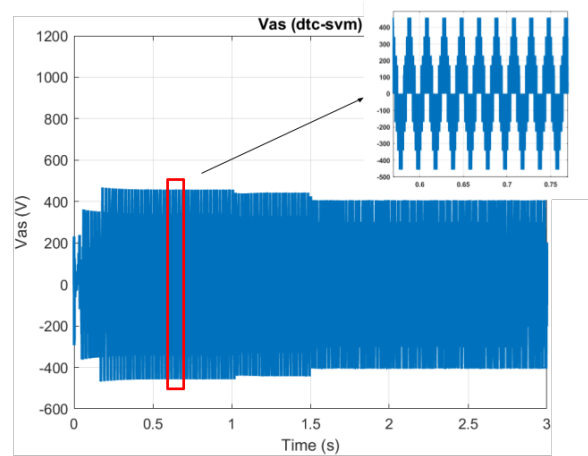
(a) Rotor speed



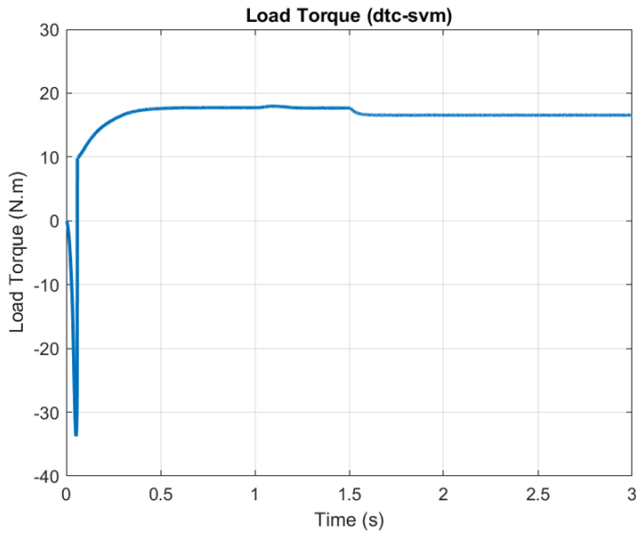
(b) Electromagnetic torque



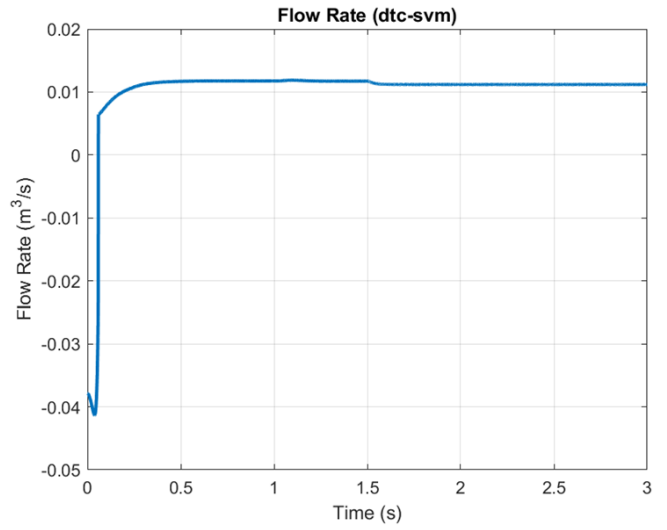
(c) Stator current



(d) Output voltage



(e) Load torque



(f) Flow rate

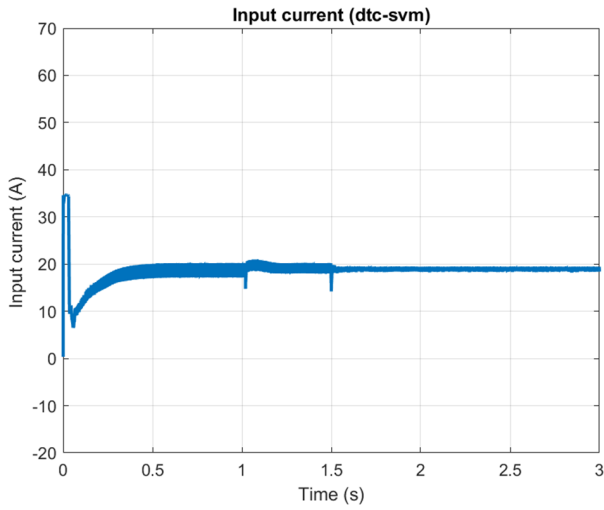
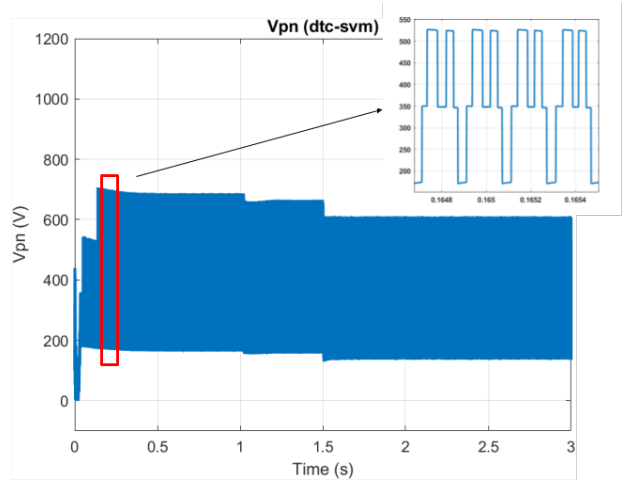


Figure 3.17: (e) Input current I_{PV}



(f) DC link voltage

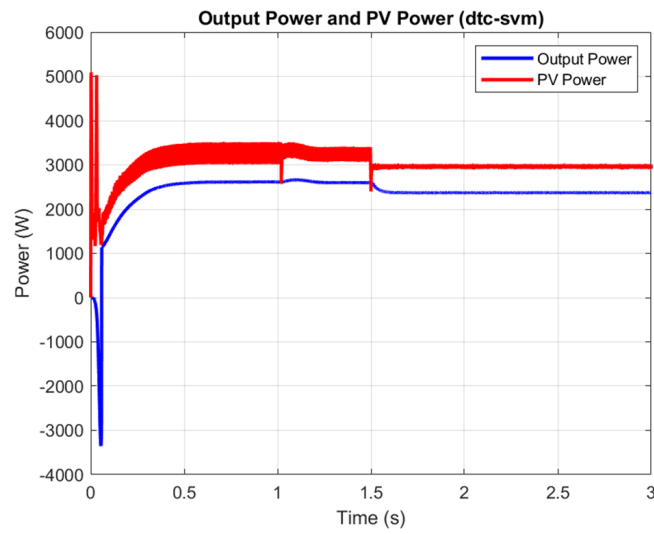
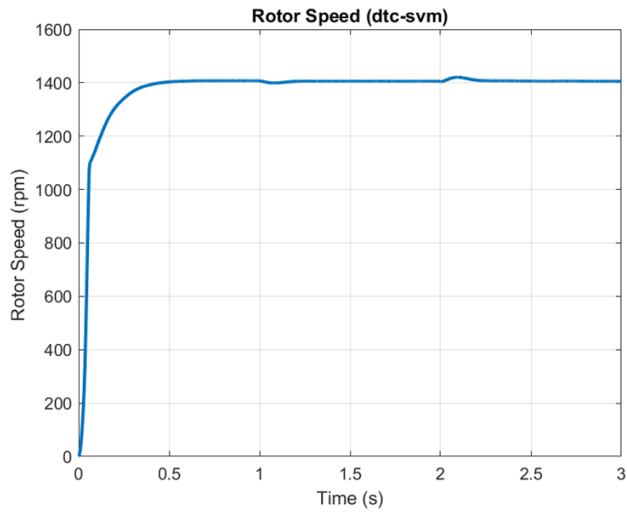
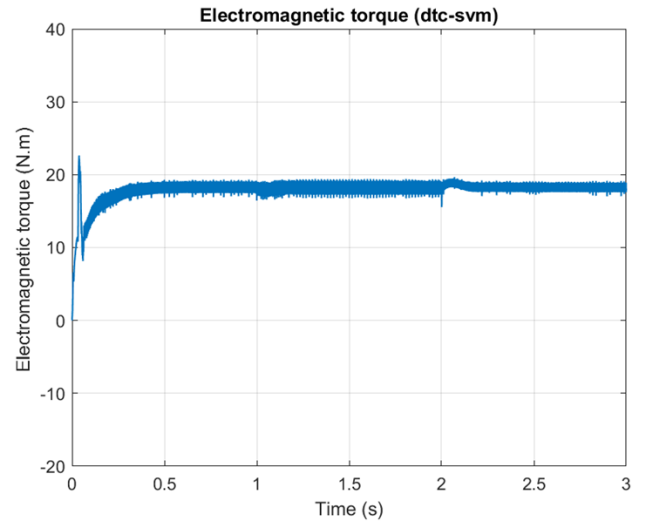


Figure 3.18: Comparison between the output power and the PV power

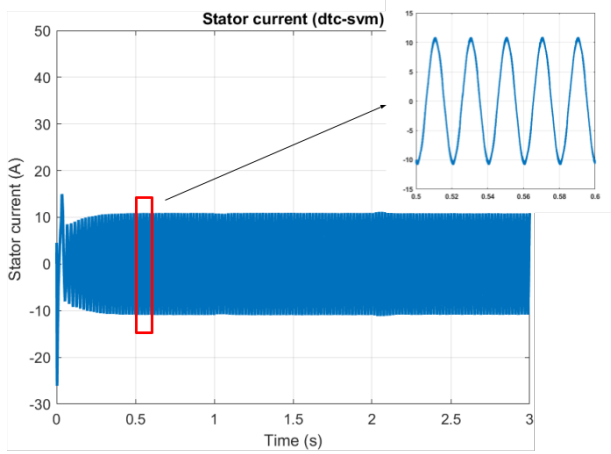
- C/ Constant irradiance ($I=1000 \text{ kW/m}^2$), variable temperature ($T=25\text{-}15\text{-}35 \text{ }^\circ\text{C}$)



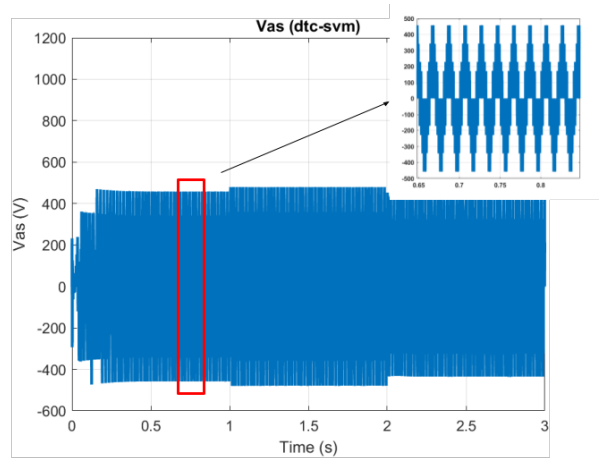
(a) Rotor speed



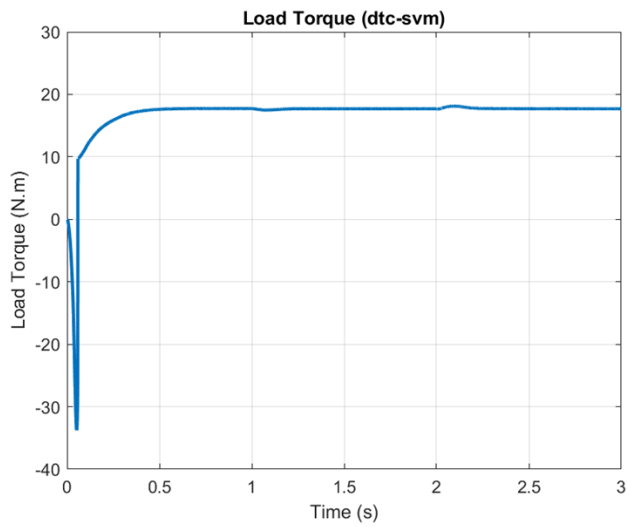
(b) Electromagnetic torque



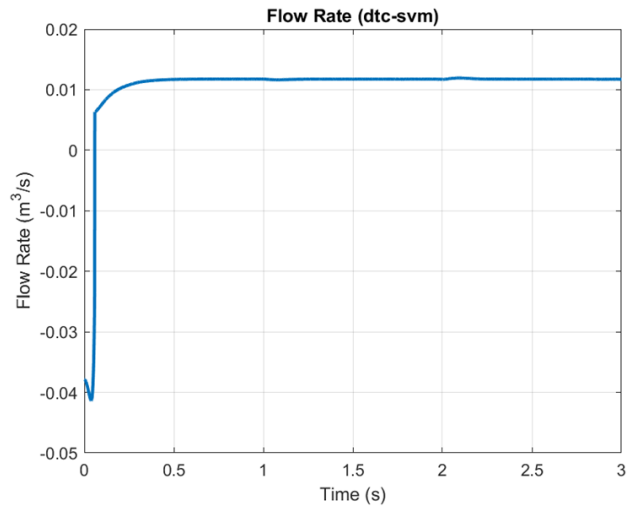
(c) Stator current



(d) Output voltage



(e) Load torque



(f) Flow rate

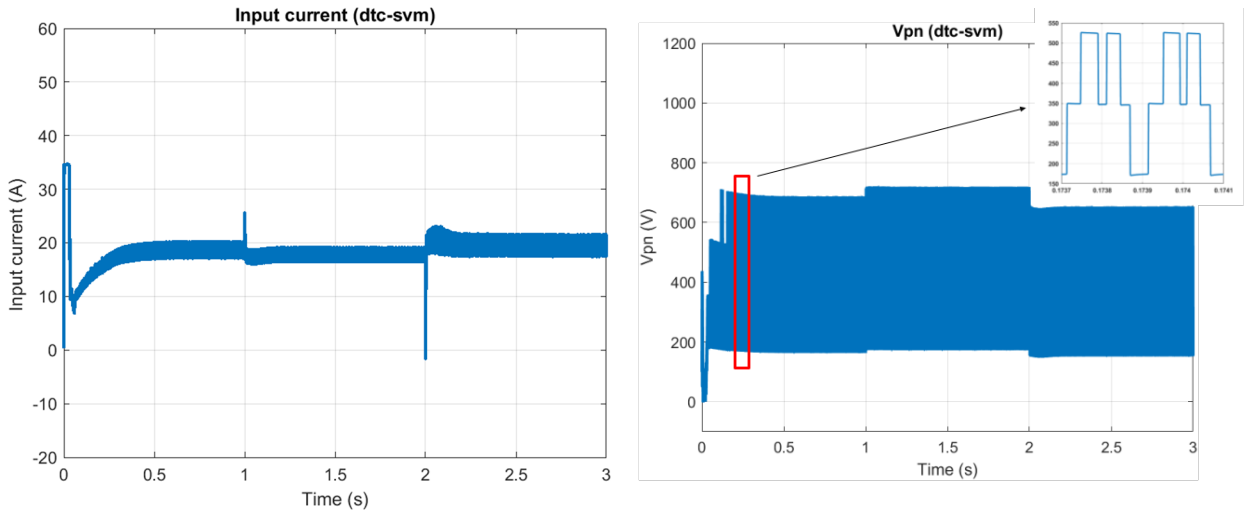


Figure 3.19: (g) Input current I_{PV}

(f) DC link voltage

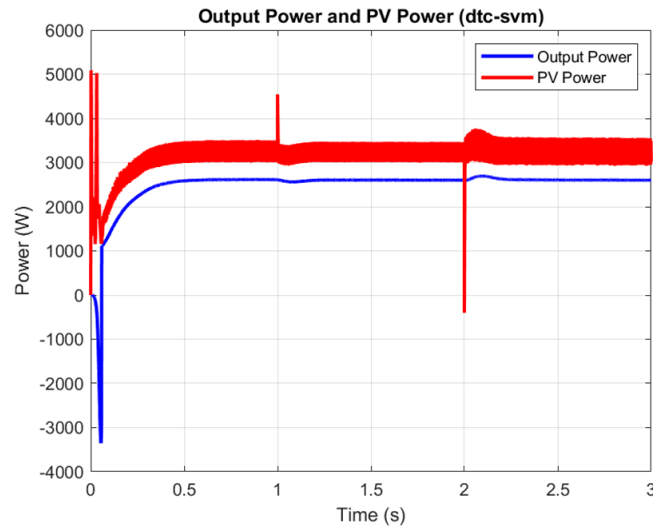


Figure 3.20: (i) Comparison between the output power and the PV power

3.1.1.1.3 Interpretation of the results

- Figure (a) illustrates the rotor speed profile over time. The motor accelerates rapidly and reaches its steady-state speed of approximately 1400 rpm with a smooth transition. No overshoot or speed ripples are observed, indicating a highly stable and refined dynamic response. This highlights the effectiveness of the DTC-SVM strategy in ensuring precise and ripple-free speed regulation.
- Figure (b) shows the evolution of the electromagnetic torque. The startup phase is well-handled, with the torque stabilizing quickly around 17 Nm without noticeable oscillations, reflecting excellent torque control and reduced switching disturbances due to the modulation technique.
- The flow rate follows the motor speed closely and reaches its required value promptly once the steady state is attained.

- The absence of oscillations in both speed and torque confirms the system's smooth mechanical behavior under DTC-SVM control.
- When powered by a PV source equipped with an MPPT algorithm, the system maintains stable and efficient operation under constant irradiance. The MPPT ensures optimal extraction of available solar power, allowing the inverter to supply adequate energy to the motor and preserve nominal performance parameters.
- Under variable irradiance conditions, a slight degradation in performance is observed. As irradiance decreases, the PV output power declines slightly, which leads to a moderate drop in the motor's speed, torque, and flow rate. Despite this, the impact remains limited, indicating good robustness of the control strategy.
- The MPPT continues to track the maximum power point accurately even at lower irradiance levels. When irradiance drops to 800 W/m² and 600 W/m², the PV system delivers power values closely corresponding to the power values obtained from the P(V) characteristics at the MPPT point which are approximately 4 kW and 2.99 kW, respectively, compared to 5.0 kW at 1000 W/m². This capability helps the system remain efficient and stable even under reduced solar input.
- In contrast, under temperature variations, the motor's behavior remains largely unaffected. Only minor fluctuations are observed in speed, torque, and flow rate, as the power generated by the PV source remains relatively stable. Consequently, the output power does not change significantly, indicating that temperature has a much less pronounced effect on the system's operation compared to irradiance.
- The DC link voltage V_{pn} at the inverter input under DTC-SVM control is shown in 3.15, 3.17, and 3.19. After a brief transient, the voltage stabilizes, confirming the effective operation of the switched capacitor-based boosting stage.
The zoomed-in waveforms highlight the multilevel structure, favorable for reliable motor operation. It is clear that the boosting level follows the controller in multilevel working mode. The DC link voltage is formed of V_{dc} and two voltage levels.
With an input voltage $V_{dc} = 176$ V, the observed output levels are approximately 176 V, 350 V, and 525 V, consistent with the relation $V_{pn} \approx (I + 1) \cdot V_{dc}$, where I is the number of switched capacitor stages. The zoomed-in waveforms highlight the multilevel structure and well-controlled ripple, favorable for reliable motor operation.
- Figures 3.17 and 3.19 shows the influence of environmental conditions on V_{pn} . A decrease in solar irradiation results in a noticeable drop in V_{pn} , while a lower temperature tends to slightly increase it. These variations align with the typical behavior of photovoltaic generators under changing weather conditions.
- The input current exhibits high current peaks, reaching approximately 900A, during the charging mode, which presents a significant limitation for SC inverters.
- The absence of high current peaks in the PV source case is due to the PV panel's inherent current-limiting nature, which prevents it from delivering the fast, high inrush current seen with low-impedance DC sources. Even if the inverter suddenly demands a large current (e.g., during SC charging), the PV panel will limit the current to its short-circuit value. This makes PV sources more forgiving for SC inverters in terms of input current stress.

3.1.1.1.4 Power Study

To assess the system's performance accurately, both input and output power must be calculated. The input power is obtained by multiplying the inverter's input current by the DC voltage provided by the PV source. The output power, on the other hand, corresponds to the mechanical power of the motor and is determined by the product of the electromagnetic torque and the rotational speed of the motor shaft.

$$P_{\text{in}} = V_{\text{in}} \times I_{\text{in}} = 3.468 \text{ kW}$$

$$P_{\text{out}} = \Omega \times T_{\text{em}} = 2.767 \text{ kW}$$

The efficiency of the system, which is defined as the ratio of output power to input power, is calculated as:

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100 = 80\%$$

This efficiency value indicates that the system is operating effectively, with a significant portion of the power generated by the PV source being successfully delivered to the load. Such performance contributes to lower energy losses, improved overall energy utilization, and increased sustainability. However, the presence of nearly 20% losses suggests that there is still room for optimization—particularly in the inverter stage, motor efficiency, and power conversion strategy—to further enhance system performance and reduce energy costs.

3.1.1.1.5 V/f Control Method

- **Case 1: DC voltage source:**

The first case evaluates the performance of the V/f control method when the system is powered by a stable DC voltage source, providing a reference scenario under ideal supply conditions. The simulation parameters for the inverter and the asynchronous motor driving the pump are listed in Table 3.4.

Table 3.4: **The parameters and values of the components in the case of a DC voltage source feeding an asynchronous motor coupled to a water pump**

Parameter	V_{dc}	f	P_n	n_n
Value	180 V	5 kHz	4 kW	1430 rpm

The simulation results corresponding to this configuration are presented below.

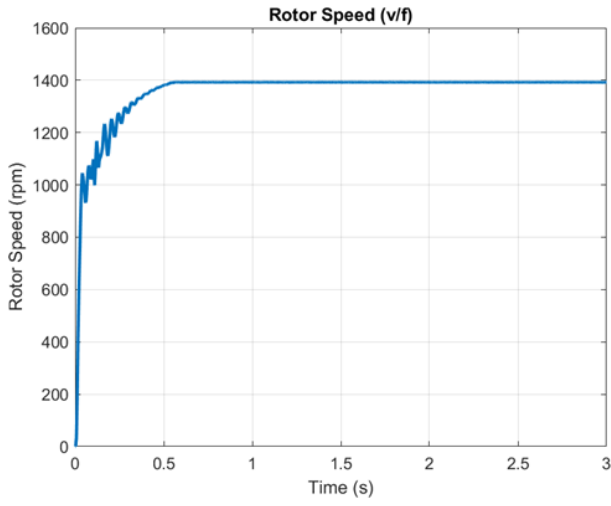


Figure 3.21: (a) Rotor speed

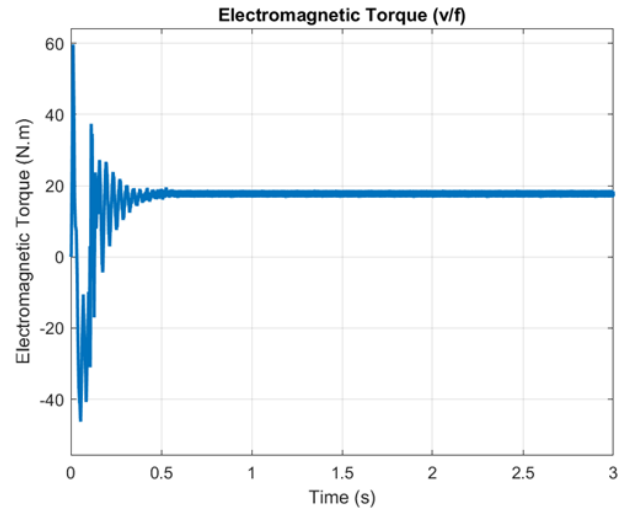


Figure 3.22: (b) Electromagnetic torque

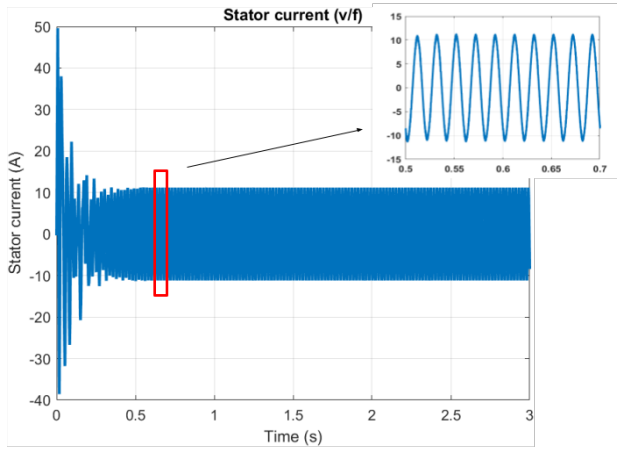


Figure 3.23: (c) Stator current

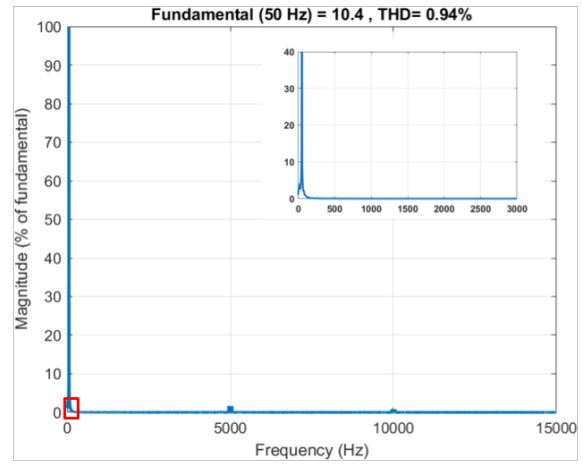


Figure 3.24: (d) The fft analysis of the output current

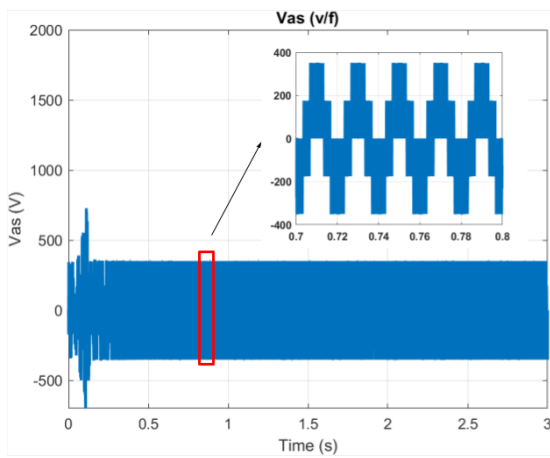


Figure 3.25: (e) Output voltage

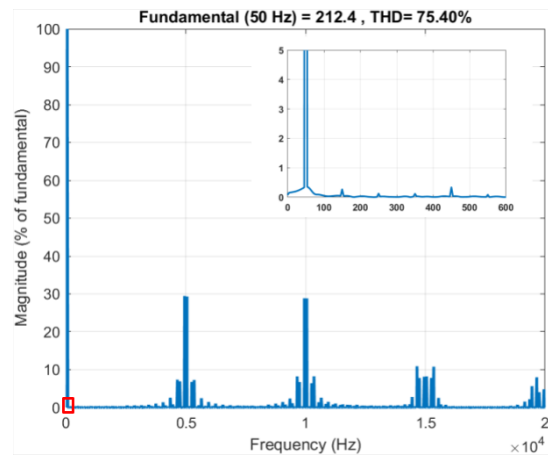


Figure 3.26: (f) The fft analysis of the output voltage

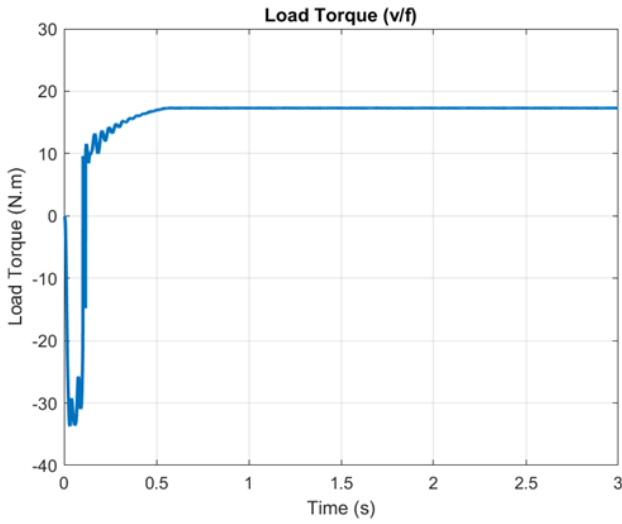


Figure 3.27: (g) Load torque

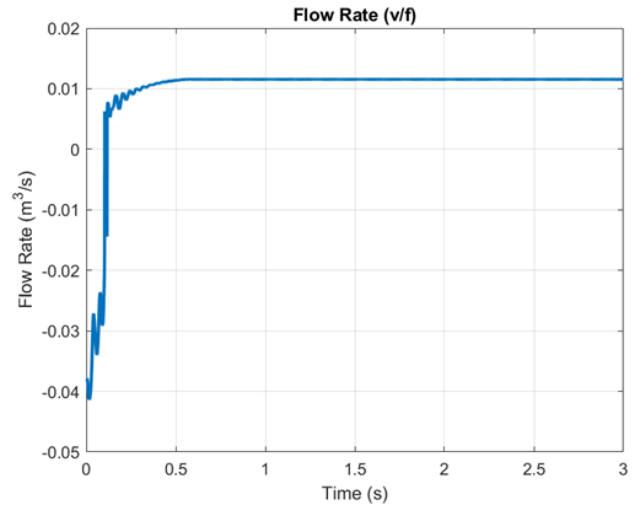


Figure 3.28: (h) Flow rate

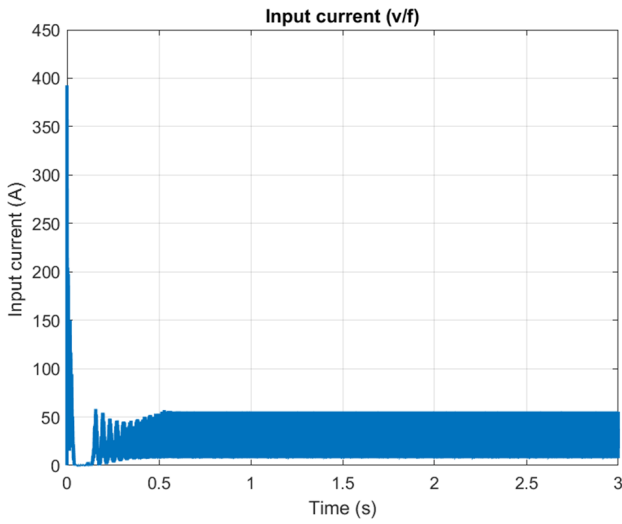


Figure 3.29: (i) Input current

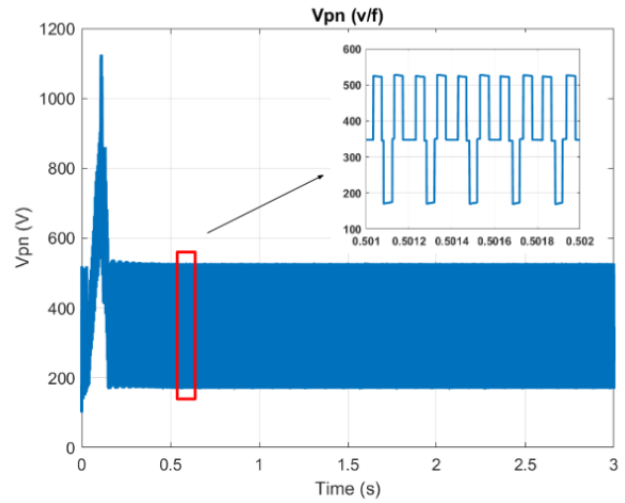


Figure 3.30: (f) DC link voltage

3.1.1.1.6 Interpretation of the results

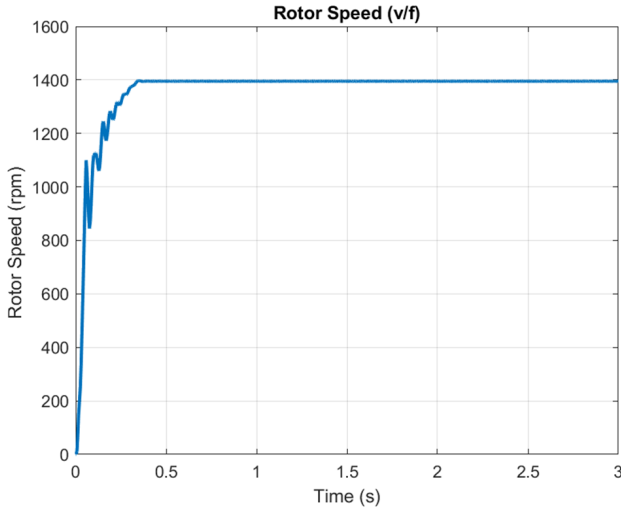
- Figure (e) shows That the output voltage waveform of the inverter is a multilevel voltage waveform with an obtained fundamental magnitude equal to 212.4 and it follows its reference which is equal to 220V. The difference between the fundamental and the reference is due to the voltage drop across the semiconductors and the capacitor of the SC inverter.
- When analyzing the output voltage harmonic spectrum, it is clear that there are no low frequency harmonics. The main harmonics are concentrated around the switching frequency (1 MHz) and its multiples while the low frequency harmonics are very low ($<0.5\%$ of the fundamental).
- Figure (c) shows the output current, which is clearly sinusoidal and has very few harmonic components. This justifies the low Total Harmonic Distortion (THD) value of 0.94%.
- When analyzing the output current harmonic spectrum shown in Figure (d), it is clear that the main harmonics are around the switching frequency which is equal to 1 MHz and its multiples. The low frequency harmonics are very low ($<0.2\%$ of the

fundamental).

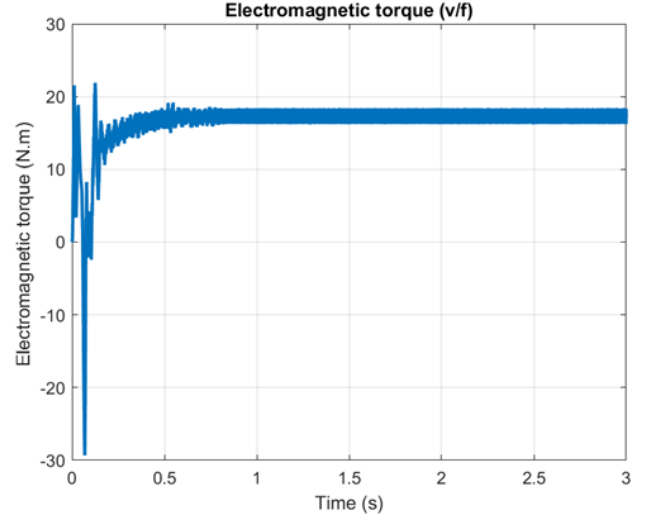
- **Case 2: PV Source with MPPT**

The second case study examines the photovoltaic (PV) system in which the proposed switched capacitor inverter supplies an asynchronous motor coupled to a pump. The Perturb and Observe (P&O) algorithm is applied to track the maximum power point of the PV source. This test aims to evaluate the performance of the v/f control strategy and assess the system's dynamic behavior under realistic operating conditions.

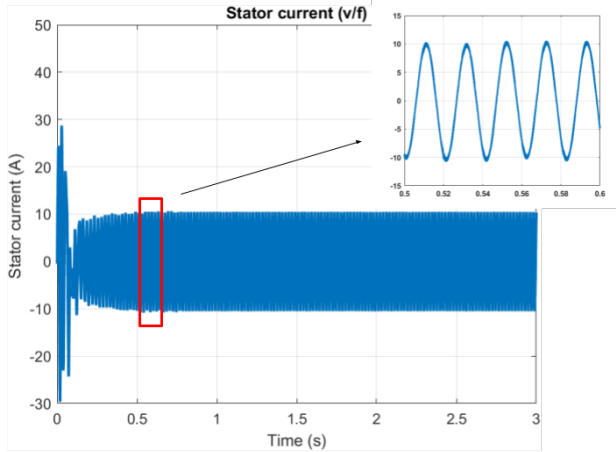
- **A/** Constant irradiance ($I=1000 \text{ kW/m}^2$) and temperature ($T=25^\circ\text{C}$)



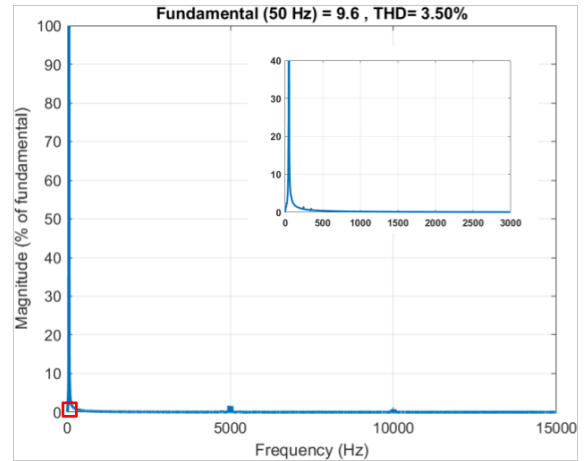
(a) Rotor speed



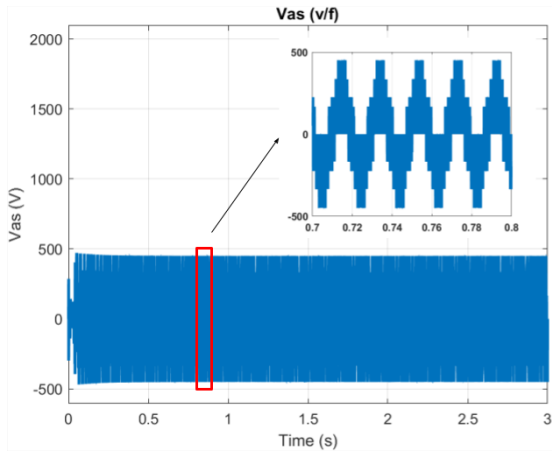
(b) Electromagnetic torque



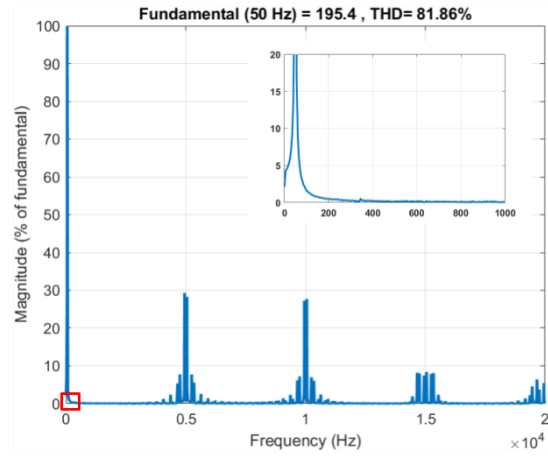
(c) Stator current



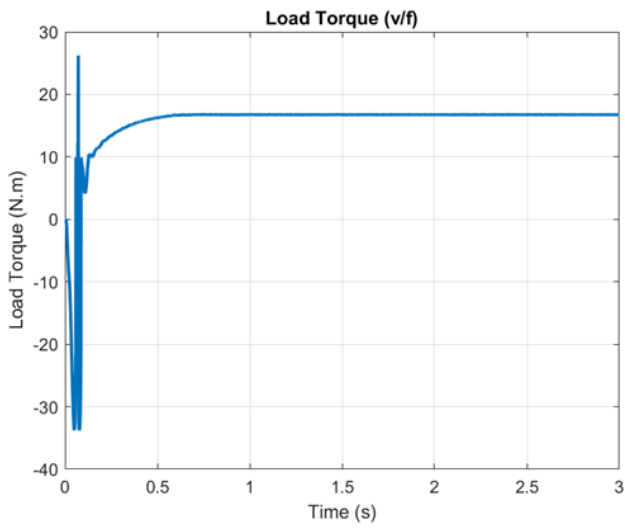
(d) The fft analysis of the output current



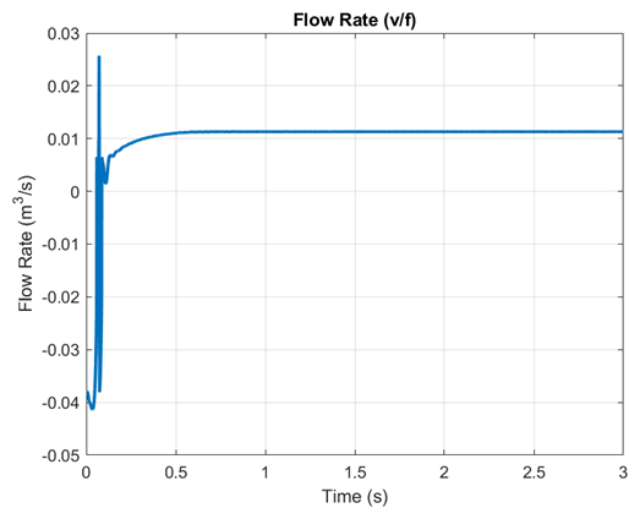
(e) Output voltage



(f) The fft analysis of the output voltage



(g) Load torque



(h) Flow rate

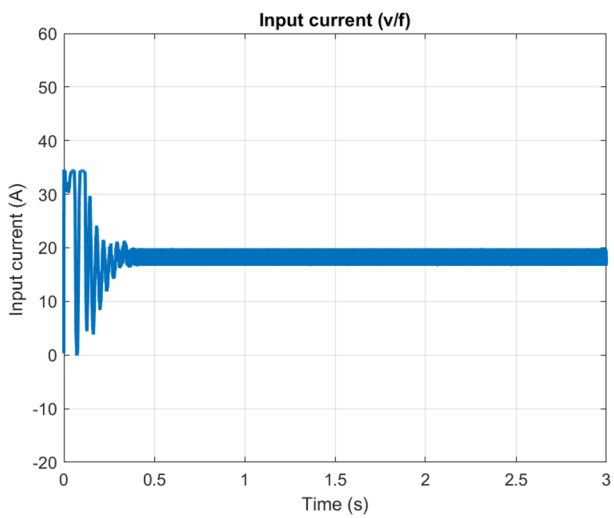
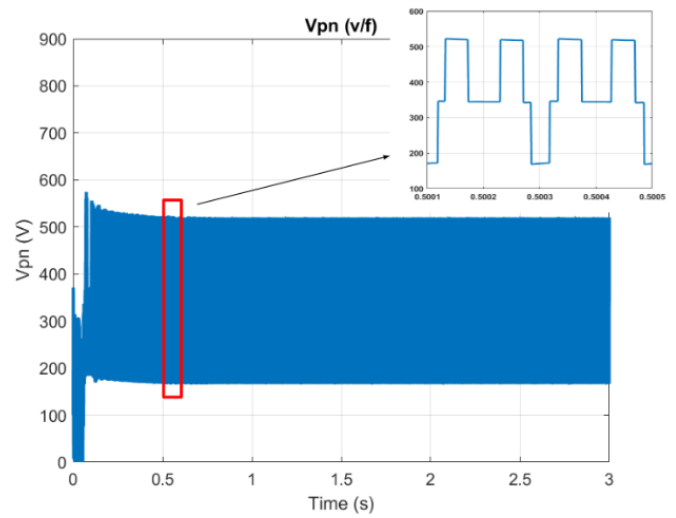


Figure 3.31: (i) Input current I_{PV}



(j) DC link voltage

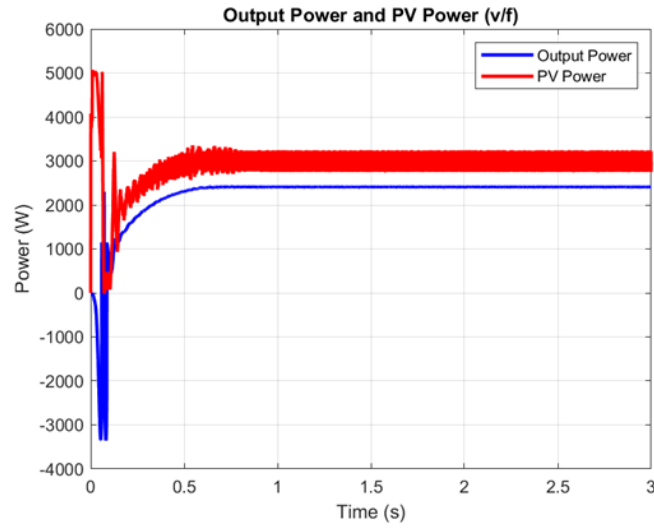
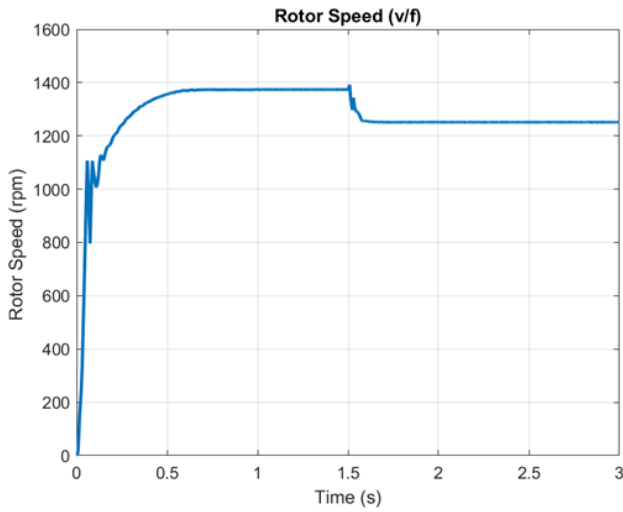
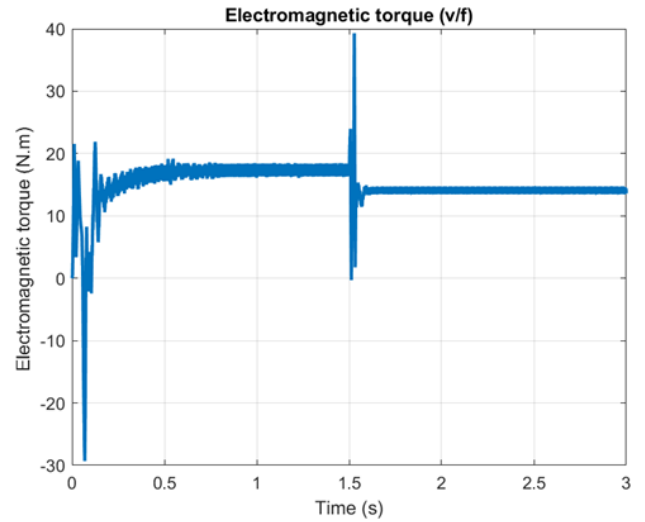


Figure 3.32: (k) Comparison between the output power and the PV power

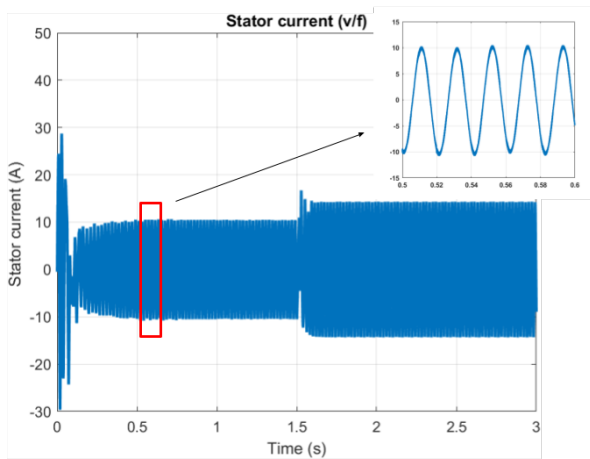
◦ **B/** Variable irradiance ($I=1000-800-600 \text{ kW/m}^2$), constant temperature ($T=25^\circ\text{C}$)



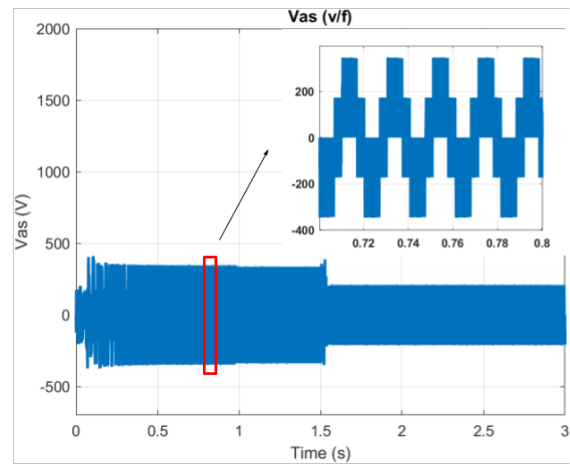
(a) Rotor speed



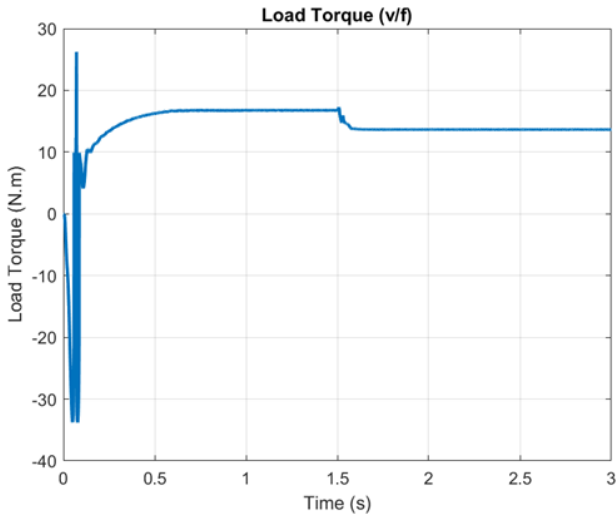
(b) Electromagnetic torque



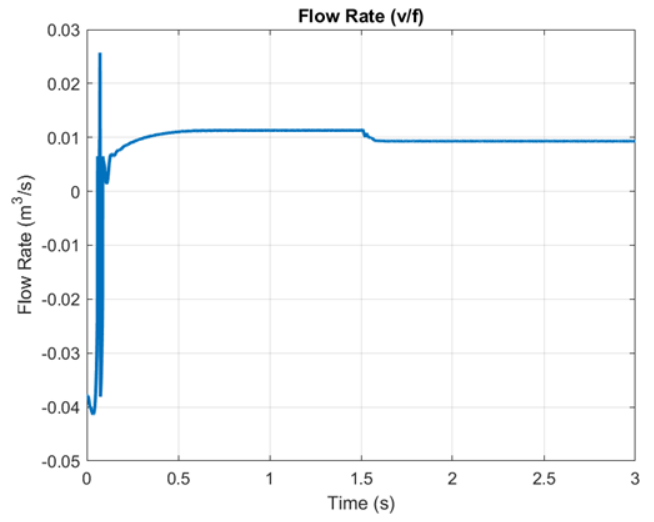
(c) Stator current



(d) Output voltage



(e) Load torque



(f) Flow rate

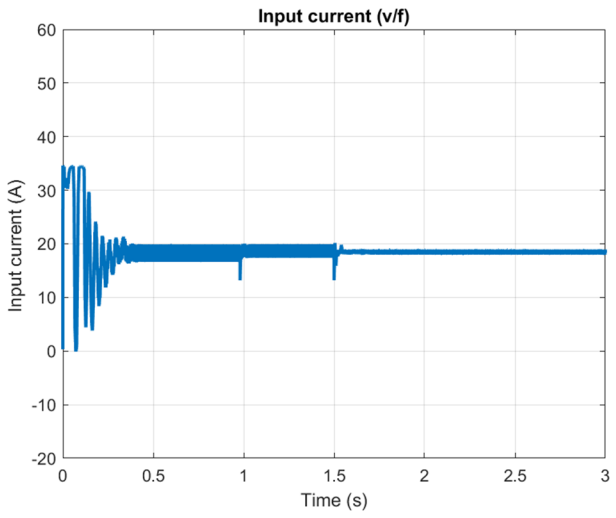
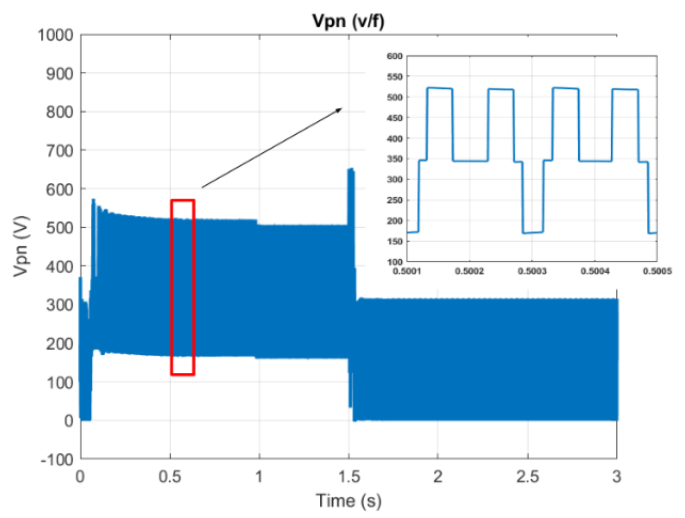


Figure 3.33: (g) Input current I_{PV}



(h) DC link voltage

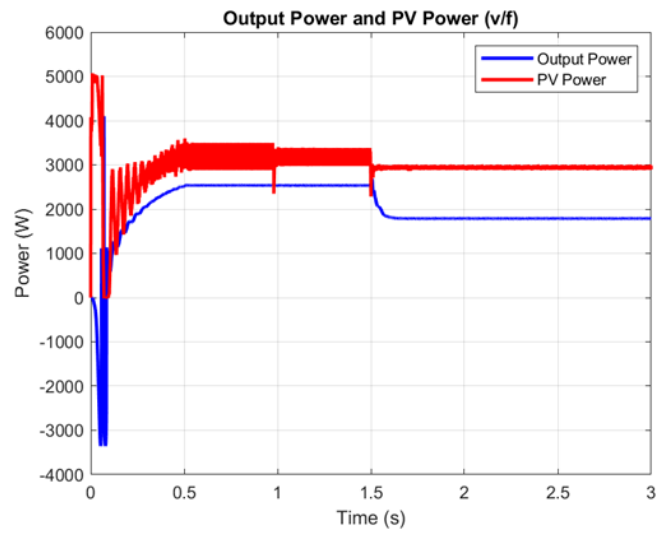
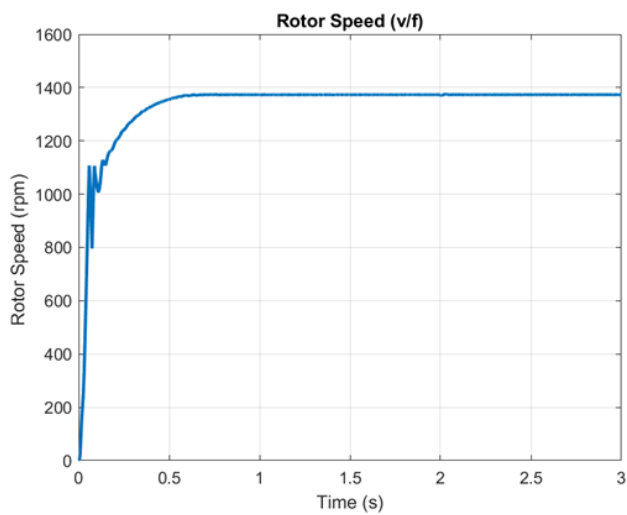
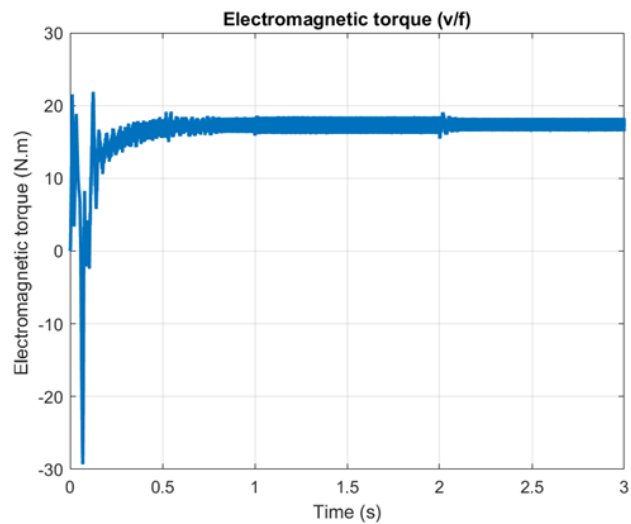


Figure 3.34: (i) Comparison between the output power and the PV power

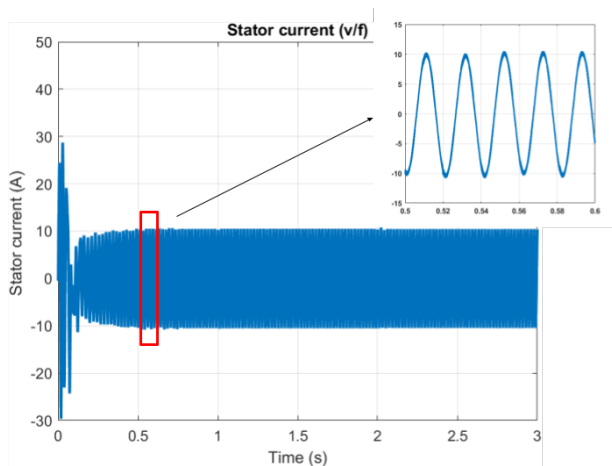
- C/ Constant irradiance ($I=1000 \text{ kW/m}^2$), variable temperature ($T=25\text{-}15\text{-}35 \text{ }^\circ\text{C}$)



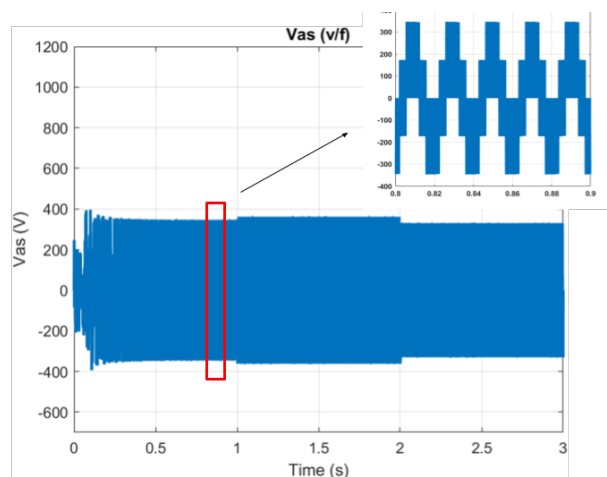
(a) Rotor speed



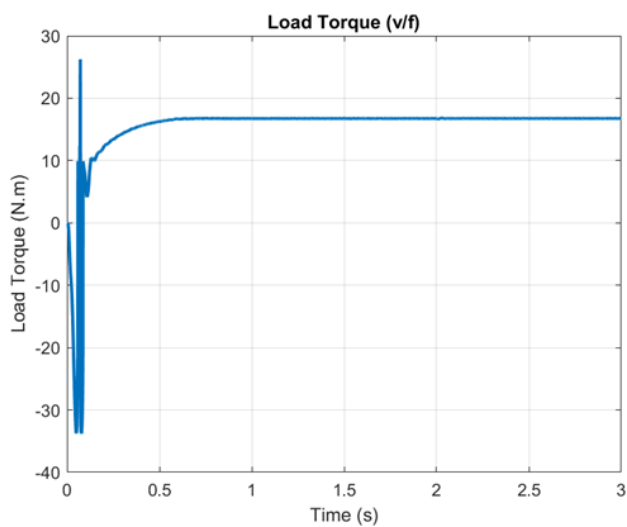
(b) Electromagnetic torque



(c) Stator current



(d) Output voltage



(e) Load torque

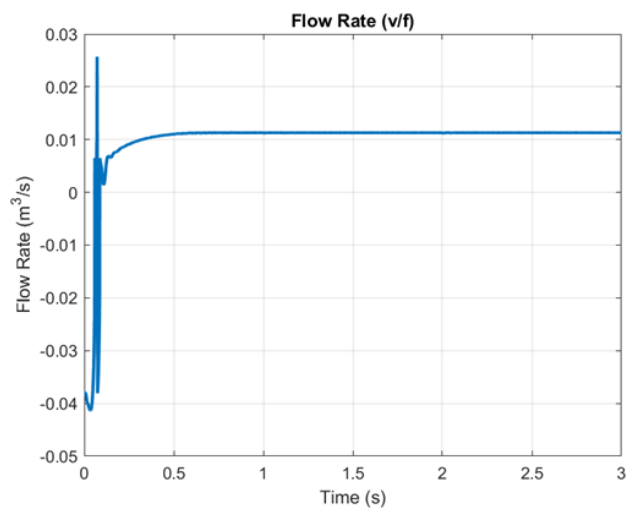


Figure 3.35: (f) Flow rate

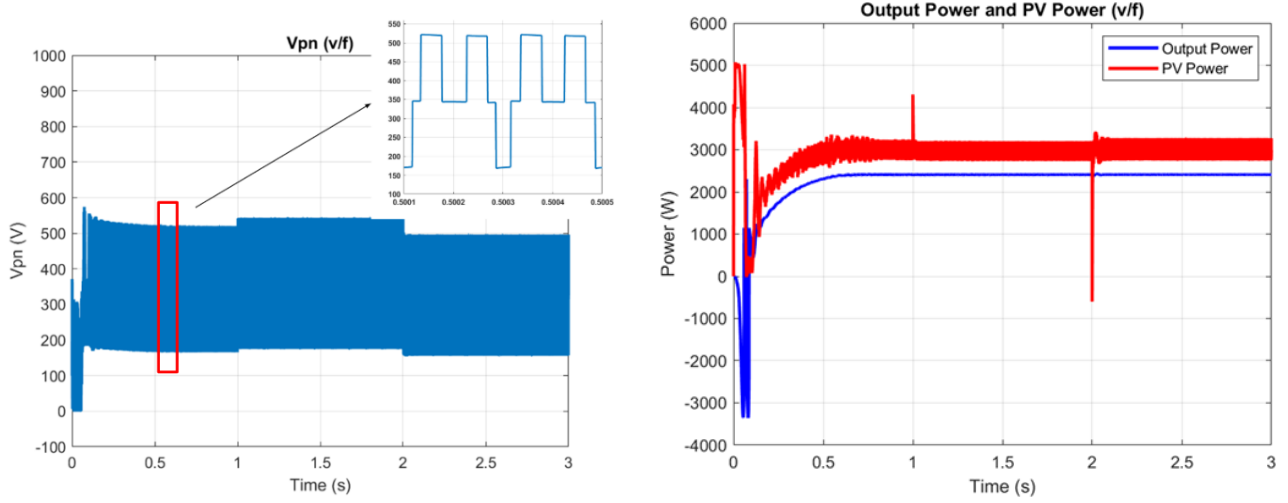


Figure 3.36: (g) Output voltage of the switched capacitor (h) Comparison between the output power and the pv power

3.1.1.1.7 Power Study

To assess the system's performance accurately, both input and output power must be calculated. The input power is obtained by multiplying the inverter's input current by the DC voltage provided by the PV source. The output power, on the other hand, corresponds to the mechanical power of the motor and is determined by the product of the electromagnetic torque and the rotational speed of the motor shaft.

$$P_{in} = V_{in} \times I_{in} = 3.155 \text{ kW}$$

$$P_{out} = \Omega \times T_{em} = 2.540 \text{ kW}$$

The efficiency of the system is defined as the ratio of output power to input power. Therefore, in this case the efficiency is:

$$\eta = \frac{P_{out}}{P_{in}} \times 100 = 81 \%$$

This efficiency value indicates that the system is operating effectively, with a significant portion of the power generated by the PV source being successfully delivered to the load. Such performance contributes to lower energy losses, improved overall energy utilization, and increased sustainability.

However, the presence of nearly 19% losses suggests that there is still room for optimization—particularly in the inverter stage, motor efficiency, and power conversion strategy—to further enhance system performance and reduce energy costs.

3.1.1.1.8 General interpretations

- ✓ Figure (a) shows the evolution of the rotor speed over time. The rotor accelerates and reaches a steady-state speed of approximately 1400 rpm, which aligns well with the required flow rate. Slight speed ripples are observed during the transient phase, before the

system stabilizes within approximately 0.6 seconds. The absence of overshoot and the rapid damping of these oscillations indicate a well-controlled and stable dynamic response.

- ✓ Figure (b) shows the electromagnetic torque response, which initially exhibits significant oscillations due to the motor's startup transient, peaking at around ± 60 Nm. These oscillations decay rapidly, and the torque stabilizes around 17 Nm, corresponding to the mechanical load. This pronounced peak is specific to the DC voltage source; it is not observed when the system is powered by the PV source, likely due to the more progressive power delivery and current-limiting characteristics of the photovoltaic system.
- ✓ The flow rate closely follows the motor's speed. Since the speed stabilizes quickly and remains constant, the flow rate also reaches and maintains its required value efficiently which is set to be $0.013 \text{ m}^3/\text{s}$.
- ✓ When introducing a PV source with MPPT, the system continues to operate efficiently under constant conditions, maintaining stable speed, torque, and flow rate. The MPPT algorithm ensures that the maximum available power is extracted from the photovoltaic source, enabling the inverter to supply sufficient energy to the motor.
- ✓ However, when the system is subjected to variable irradiance, the simulation results clearly show a drop in performance. As irradiance decreases, the power generated by the PV source is reduced, limiting the energy available at the inverter input. As a result, the inverter delivers less power to the motor, leading to a decline in output current and a corresponding decrease in rotor speed. The electromagnetic torque also decreases, although it briefly peaks at the moment the irradiance starts to fall, due to the system's transient response. This overall reduction in speed and torque leads to a proportional drop in the flow rate and in the mechanical output power. These results highlight the system's sensitivity to irradiance fluctuations, even when equipped with MPPT, as the available solar energy directly governs the performance of the drive.
- ✓ Nevertheless, the MPPT controller effectively tracks the maximum power point of the PV curve even when the irradiance drops to 800 W/m^2 and 600 W/m^2 , ensuring that the operating point remains close to the MPP. At these levels, the maximum available power is approximately 4 kW and 2.99 kW, respectively, compared to 5 kW at 1000 W/m^2 . This allows the system to maintain relatively efficient operation despite reduced solar input.
- ✓ In contrast, under temperature variations, the motor's behavior remains largely unaffected. Only minor fluctuations are observed in speed, torque, and flow rate, as the power generated by the PV source remains relatively stable. Consequently, the output power does not change significantly, indicating that temperature has a much less pronounced effect on the system's operation compared to irradiance.
- ✓ The DC link voltage V_{pn} at the inverter input under V/f control is shown in Figures 3.30, 3.31, 3.33, and 3.36. After a brief transient, the voltage stabilizes, confirming the effective operation of the switched capacitor-based boosting stage. The zoomed-in waveforms highlight the multilevel structure, favorable for reliable motor operation. It is clear that the boosting level follows the controller in multilevel working mode. The DC link voltage is formed of V_{dc} and two voltage levels. With an input voltage $V_{dc} = 178 \text{ V}$, the observed output levels are approximately 178 V, 350 V, and 520 V, consistent with the relation $V_{pn} \approx (I + 1) \cdot V_{dc}$, where I is the number of switched capacitor stages. The zoomed-in waveforms highlight the multilevel structure and well-controlled ripple, favorable for reliable motor operation.

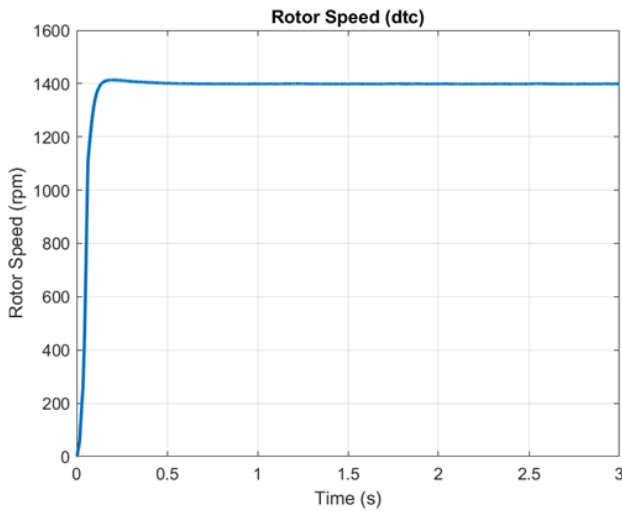
- ✓ Figures 3.33 and 3.36 shows the influence of environmental conditions on V_{pn} . A decrease in solar irradiation results in a noticeable drop in V_{pn} , while a lower temperature tends to slightly increase it. These variations align with the typical behavior of photovoltaic generators under changing weather conditions.
- ✓ The input current exhibits high current peaks, reaching approximately 900A, during the charging mode, which presents a significant limitation for SC inverters.
- ✓ The absence of high current peaks in the PV source case is due to the PV panel's inherent current-limiting nature, which prevents it from delivering the fast, high inrush current seen with low-impedance DC sources. Even if the inverter suddenly demands a large current (e.g., during SC charging), the PV panel will limit the current to its short-circuit value. This makes PV sources more forgiving for SC inverters in terms of input current stress.

3.1.1.1.9 DTC Control Method

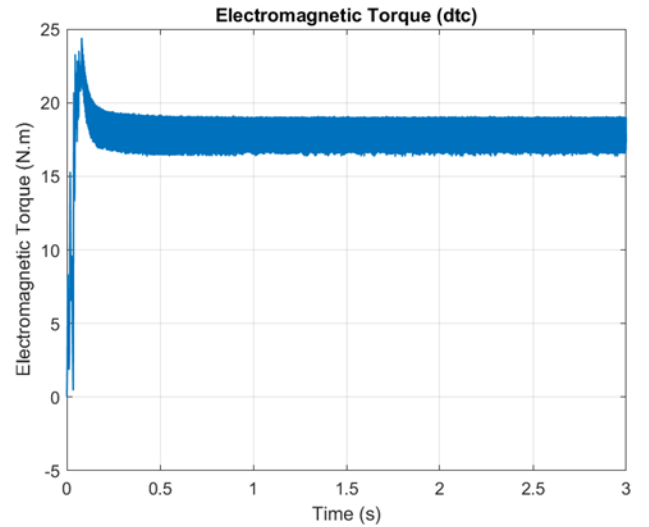
- **Case of a PV source with MPPT:**

The case study examines the photovoltaic (PV) system in which the proposed switched capacitor inverter supplies an asynchronous motor coupled to a pump. The Incremental Conductance (IC) algorithm is applied to track the maximum power point of the PV source. This test aims to evaluate the performance of the v/f control strategy and assess the system's dynamic behavior under realistic operating conditions.

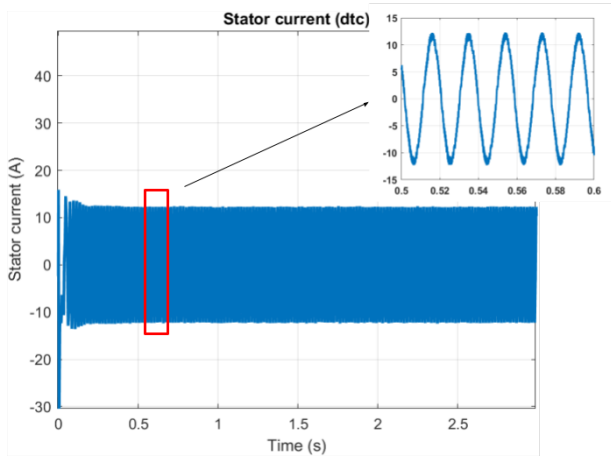
* **A/** Constant irradiance ($I=1000 \text{ kW/m}^2$) and temperature ($T=25^\circ\text{C}$)



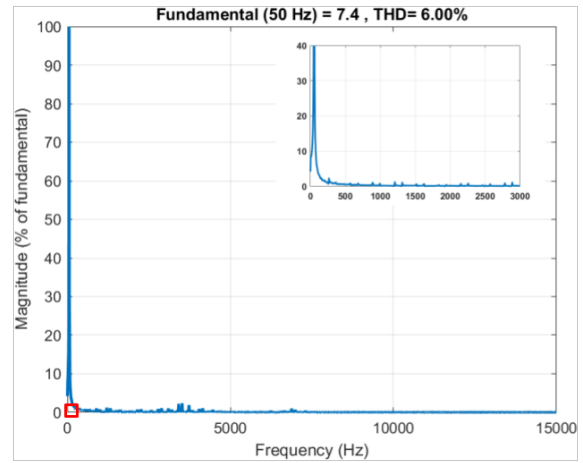
(a) Rotor speed



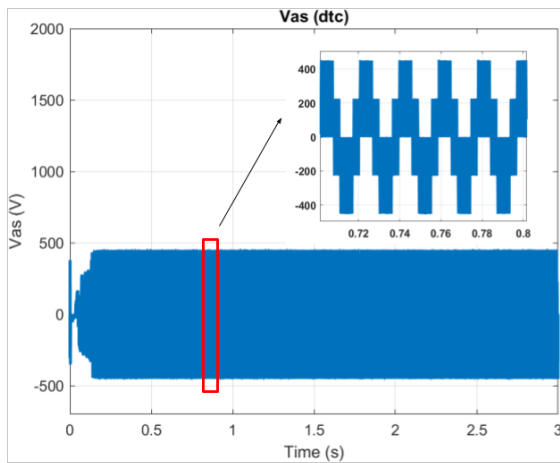
(b) Electromagnetic torque



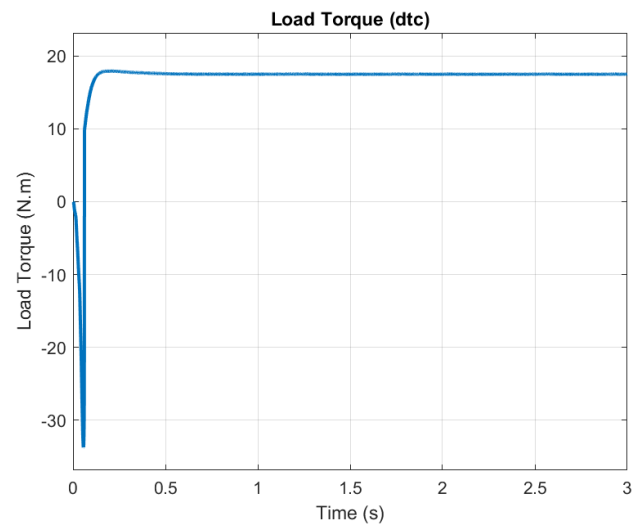
(c) Stator current



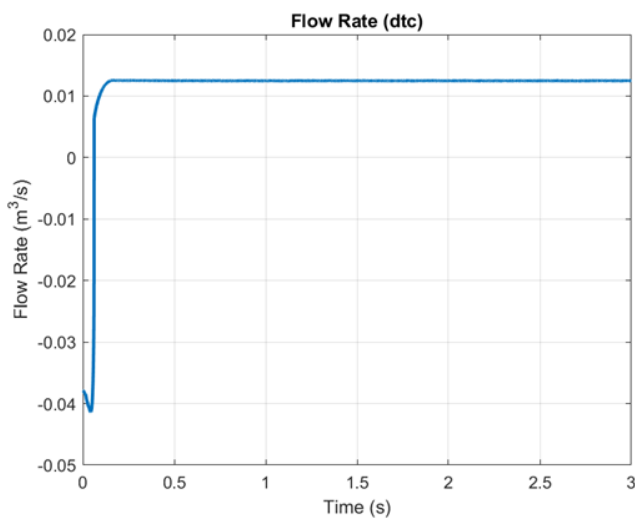
(d) The fft analysis of the output current



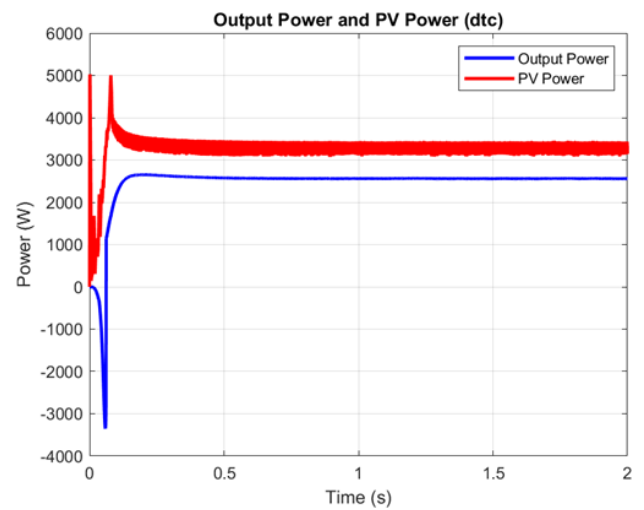
(e) Output voltage



(f) Load torque



(g) Flow rate



(h) Comparison between the output power and the pv power

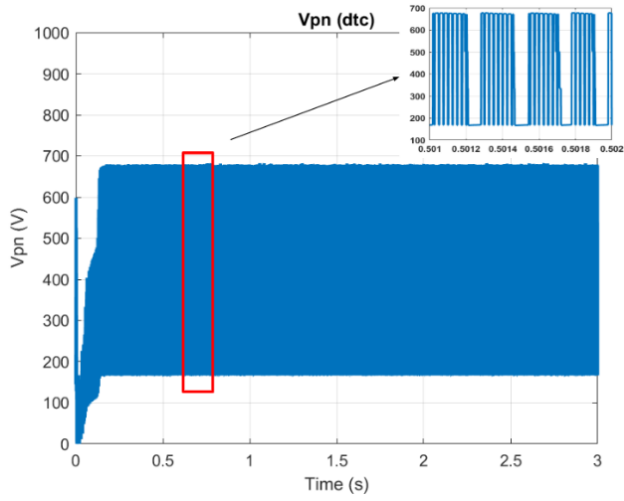


Figure 3.37: (i) DC link voltage

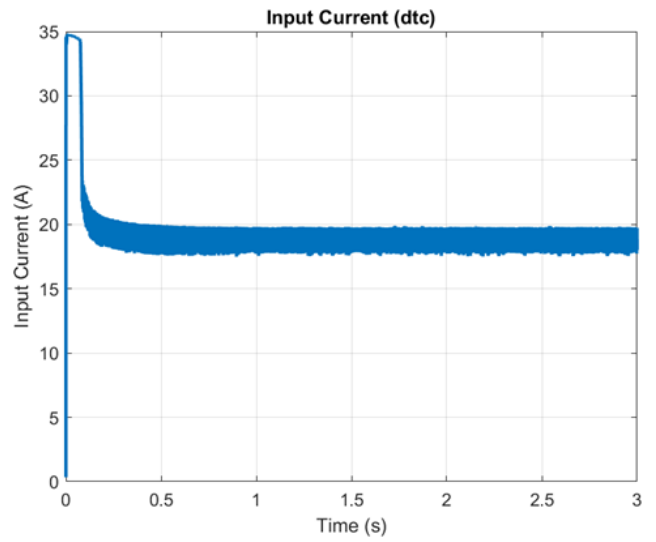


Figure 3.38: (f) Input current

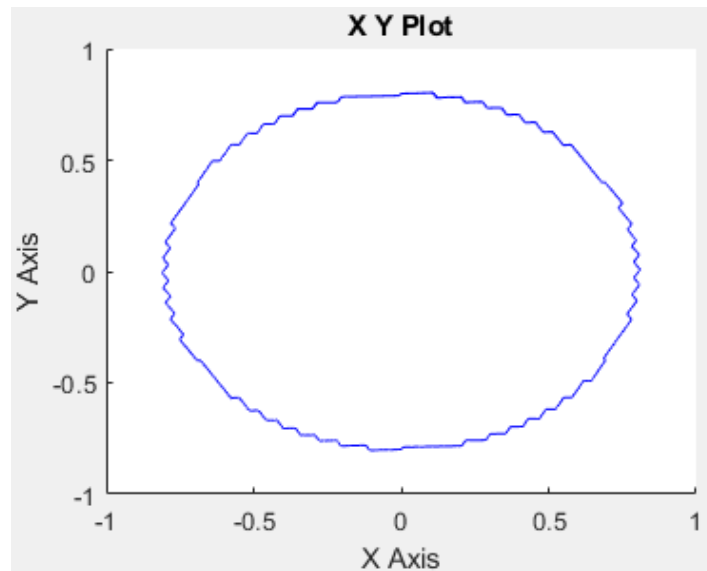
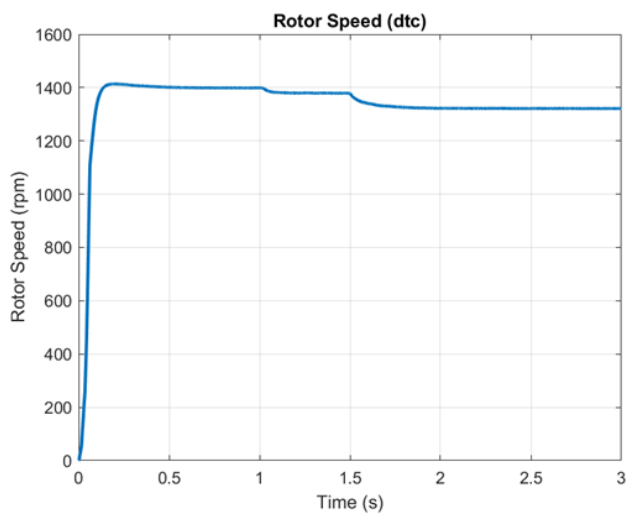
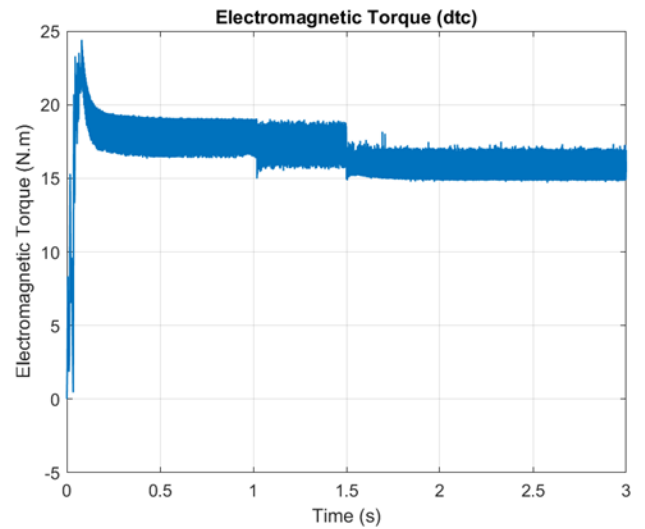


Figure 3.39: stator flux

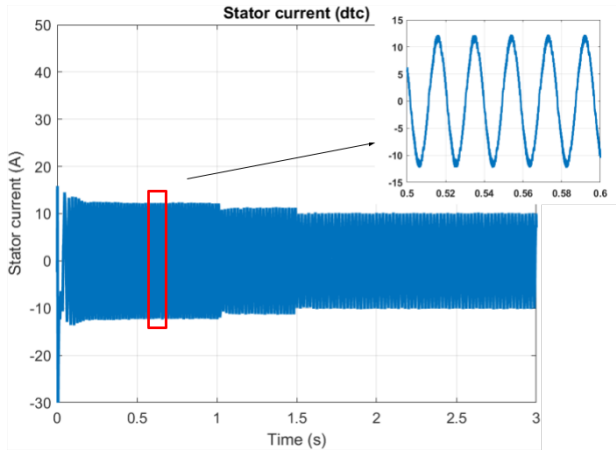
* **B/** Variable irradiance ($I=1000-800-600 \text{ kW/m}^2$), constant temperature ($T=25^\circ\text{C}$)



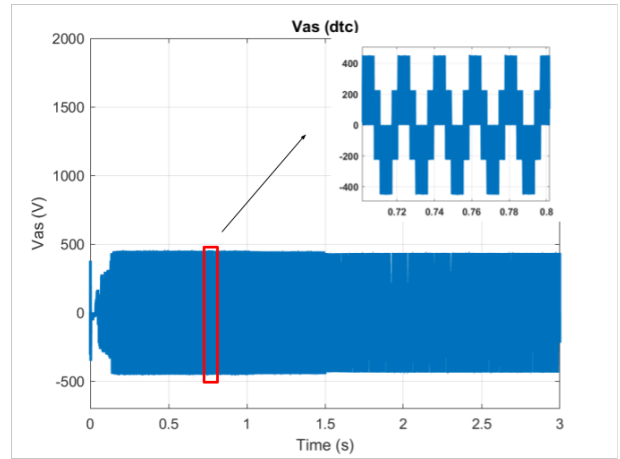
(a) Rotor speed



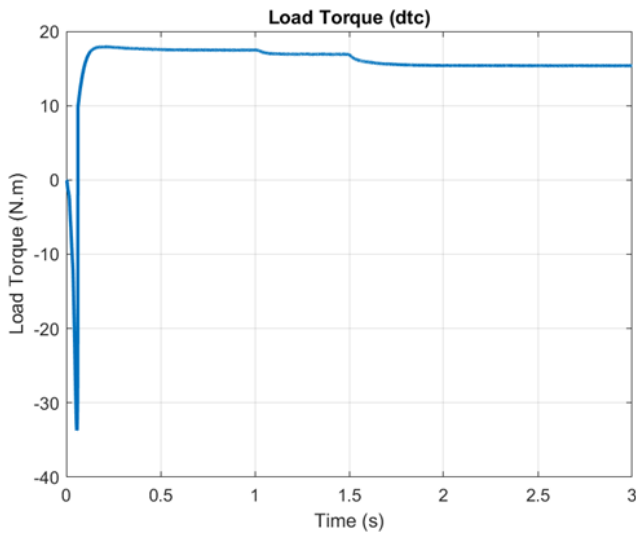
(b) Electromagnetic torque



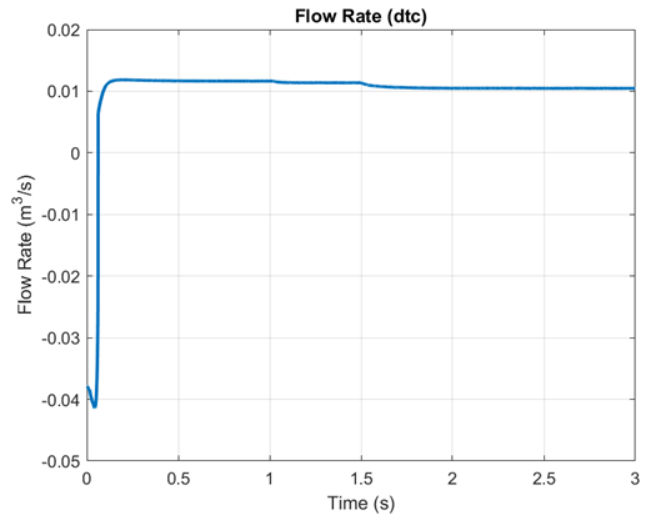
(c) Stator current



(d) Output voltage



(e) Load torque



(f) Flow rate

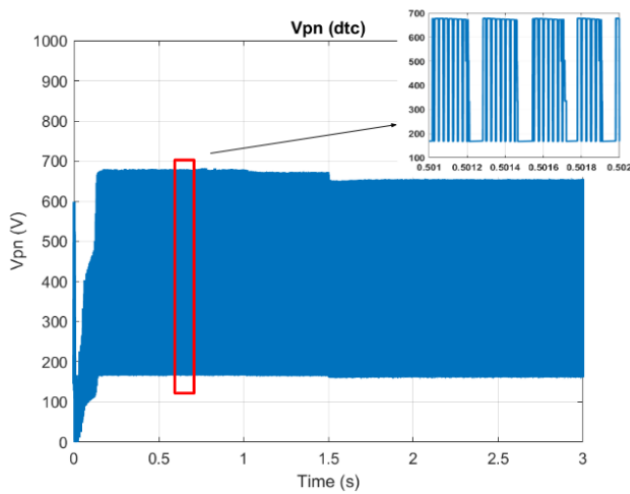
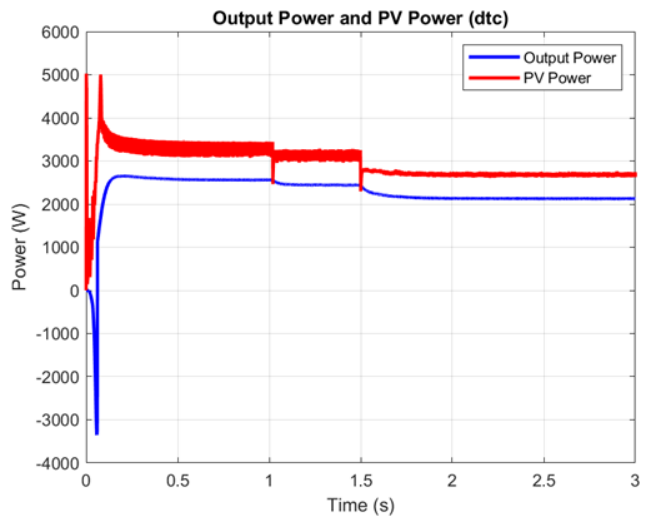
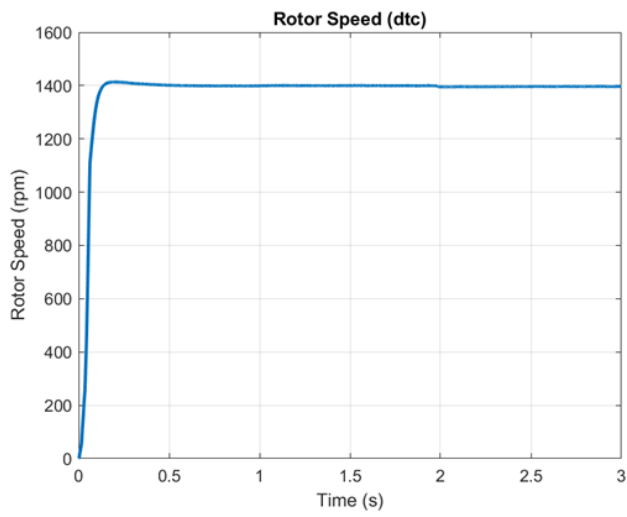


Figure 3.40: (g) DC link voltage

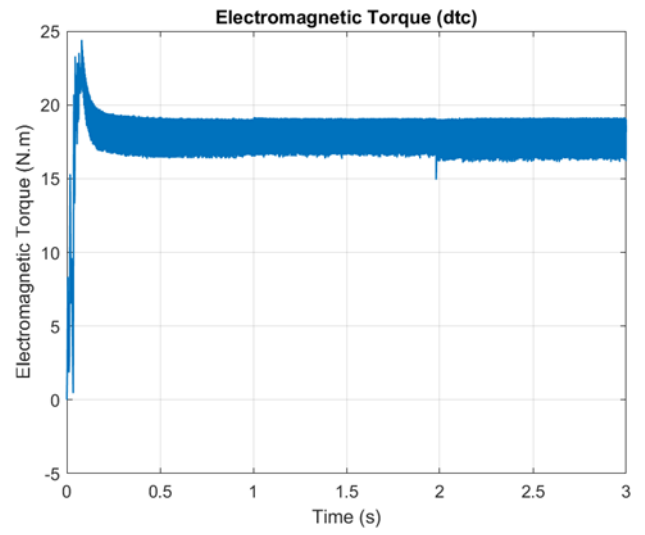


(h) Comparison between the output power and the pv power

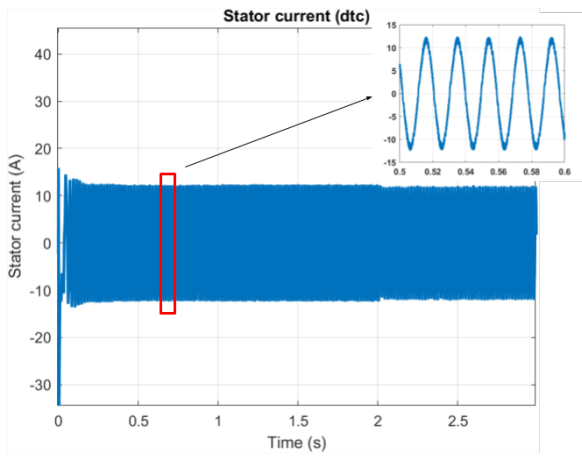
* C/ Constant irradiance ($I=1000 \text{ kW/m}^2$), variable temperature ($T=25-15-35 \text{ }^\circ\text{C}$)



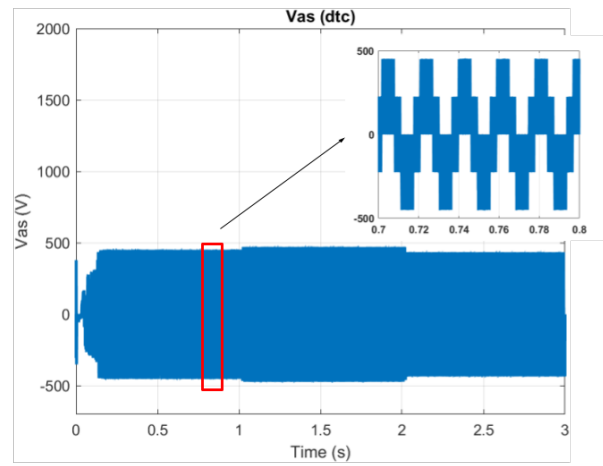
(a) Rotor speed



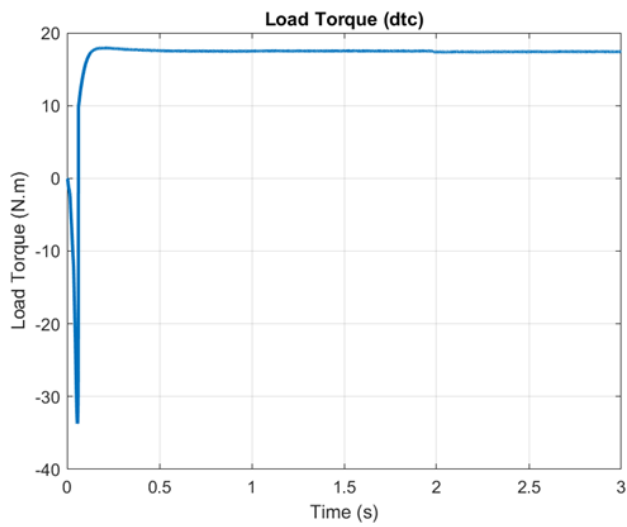
(b) Electromagnetic torque



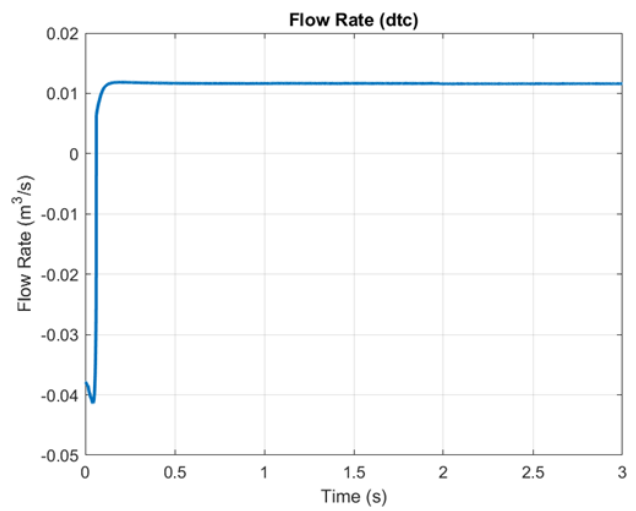
(c) Stator current



(d) Output voltage



(e) Load torque



(f) Flow rate

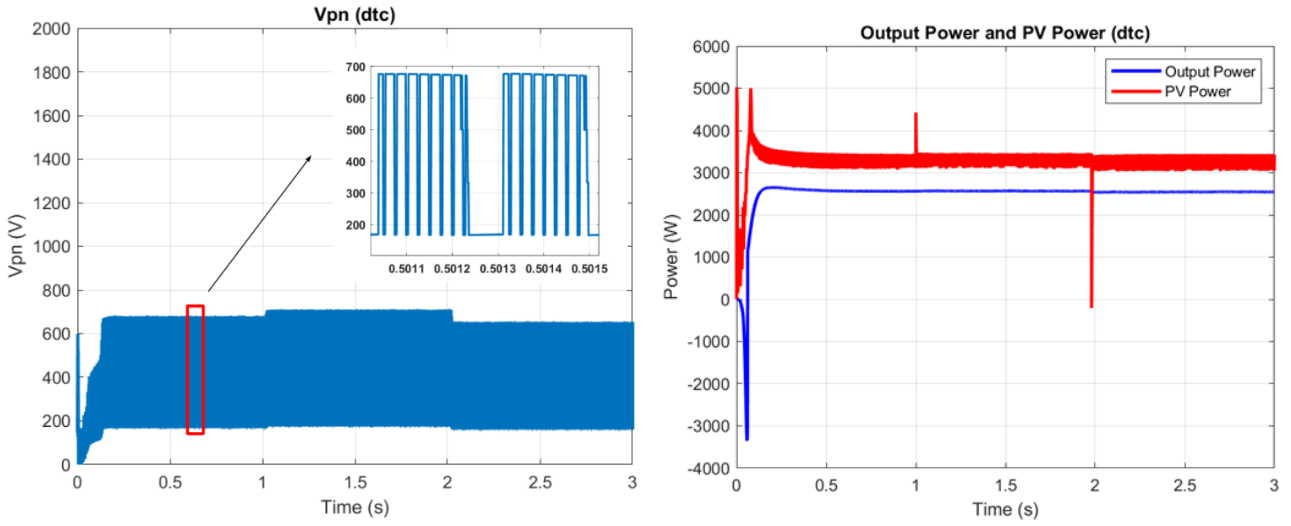


Figure 3.41: (g) DC link voltage

(g) Comparison between the output power and the pv power

3.1.1.1.10 Interpretation of the results

- The Figure (c) shows the output current, which is clearly sinusoidal and has very few harmonic components. This justifies the low Total Harmonic Distortion (THD) value of 2.06%.
- When analyzing the output current harmonic spectrum shown in Figure (d), it is clear that the main harmonics are around the switching frequency which is equal to 1 MHz and its multiples. The low frequency harmonics are very low ($<0.2\%$ of the fundamental)
- Figure (a) shows the evolution of the rotor speed over time. The motor accelerates quickly and reaches its steady-state speed of approximately 1400 rpm with no observable overshoot. The dynamic response is sharp and well-damped, with a smooth convergence and no significant speed ripples, reflecting the effectiveness of the DTC strategy in delivering fast and accurate control.
- Figure (b) presents the electromagnetic torque response. During the startup phase, a peak of approximately 24 Nm is observed as the motor accelerates. The torque then stabilizes around 17 Nm, corresponding to the mechanical load. In steady-state operation, slight ripples persist, which are characteristic of DTC due to its direct switching nature and lack of modulation.
- The flow rate, closely tied to the motor speed, rises rapidly and reaches its required value once the system stabilizes.
- When powered by a PV source with MPPT under constant irradiance and temperature, the system operates efficiently, maintaining stable values of speed, torque, and flow rate. The MPPT algorithm ensures continuous tracking of the maximum power point, enabling the inverter to deliver sufficient energy to the motor. Under variable irradiance conditions, simulation results reveal a noticeable decline in performance. As irradiance decreases, the power output of the PV source drops, reducing the energy supplied to the inverter. This leads to a lower output current and consequently, a drop in rotor speed, torque, and flow rate. The torque may exhibit a brief peak during the transition phase before settling at a reduced value. Despite these changes, The MPPT continues to track the maximum power point accurately even at lower irradiance levels. When irradiance drops to 800 W/m^2

and 600 W/m², the PV system delivers power values closely corresponding to the power values obtained from the P(V) characteristics at the MPPT point which are approximately 4 kW and 2.99 kW, respectively, compared to 5.0 kW at 1000 W/m². This ensures that the DTC-controlled system continues to operate with high responsiveness and maintains relatively efficient performance even under fluctuating solar input.

- When the temperature varies, a slight decrease in output power is observed. This is due to the temperature dependence of the PV module's voltage, which slightly reduces the available power. Consequently, minor drops occur in speed, torque, and flow rate, indicating that temperature does have an observable effect on system behavior under DTC control, although less drastic than irradiance variations.
- The stator flux closely tracks its reference value ($\phi_{ref} = 0.8$ Wb) while remaining within the hysteresis band. Moreover, the evolution of the flux vector in the (α, β) plane describes a nearly perfect circular trajectory, reflecting the effectiveness of the DTC strategy in maintaining constant flux magnitude and proper orientation.
- The DC link voltage V_{pn} at the inverter input under DTC control is shown in Figures 3.37, 3.40, 3.41, and 3.36. After a brief transient, the voltage stabilizes, confirming the effective operation of the switched capacitor-based boosting stage. The zoomed-in waveforms highlight the multilevel structure, favorable for reliable motor operation. It is clear that the boosting level follows the controller in multilevel working mode. The DC link voltage is formed of V_{dc} and a voltage level. With an input voltage $V_{dc} = 179$ V, the observed output levels are approximately 179 V and 680 V, consistent with the relation $V_{pn} \approx (I + 1) \cdot V_{dc}$, where I is the number of switched capacitor stages. The zoomed-in waveforms highlight the multilevel structure and well-controlled ripple, favorable for reliable motor operation.
- Figures 3.40 and 3.41 shows the influence of environmental conditions on V_{pn} . A decrease in solar irradiation results in a noticeable drop in V_{pn} , while a lower temperature tends to slightly increase it. These variations align with the typical behavior of photovoltaic generators under changing weather conditions.
- Figure 3.38 presents the input current waveform. A peak of approximately **35 A** is observed during the startup phase, followed by stabilization around **20 A** in steady-state operation. This behavior corresponds to the typical inrush current drawn by the motor at startup before settling under the applied load.

3.1.1.1.11 Power Study

To assess the system's performance accurately, both input and output power must be calculated. The input power is obtained by multiplying the inverter's input current by the DC voltage provided by the PV source. The output power, on the other hand, corresponds to the mechanical power of the motor and is determined by the product of the electromagnetic torque and the rotational speed of the motor shaft.

$$P_{in} = V_{in} \times I_{in} = 3.3 \text{ kW}$$

$$P_{out} = \Omega \times T_{em} = 2.58 \text{ kW}$$

The efficiency of the system is defined as the ratio of output power to input power. Therefore, in this case, the efficiency is:

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100 = 78 \%$$

This result indicates that the system is operating effectively, with a substantial portion of the power generated by the PV source being successfully delivered to the mechanical load. However, the remaining 22% represents losses—primarily due to power conversion inefficiencies, inverter switching, and motor characteristics—highlighting potential areas for optimization.

3.1.2 Comparative Analysis of the Control Methods

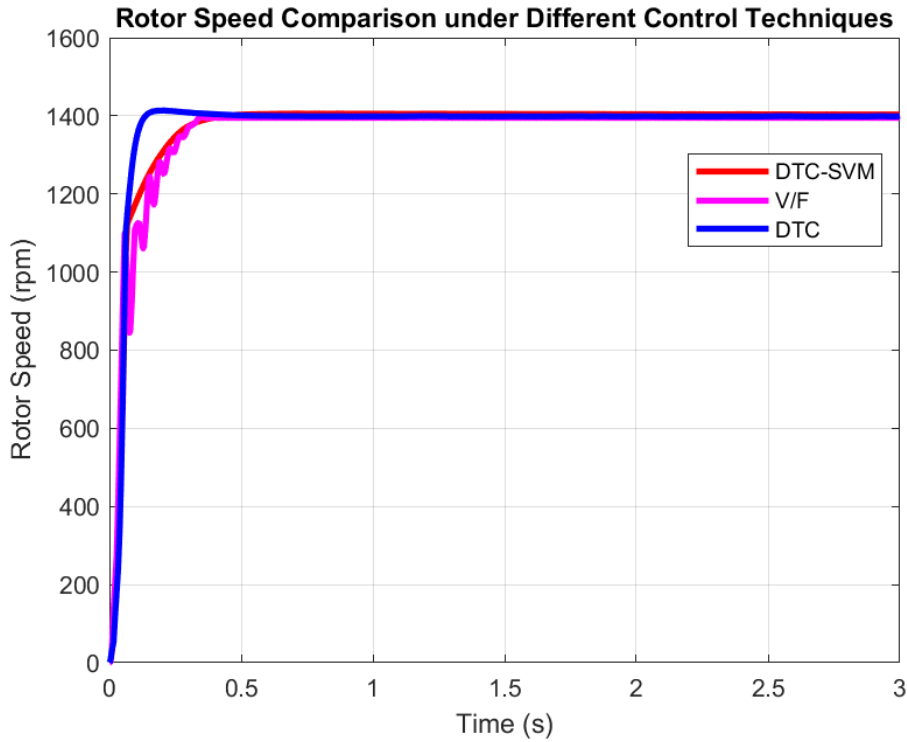


Figure 3.42: Rotor speed response for V/f, DTC, and DTC-SVM control

- Figure 3.42 illustrates the rotor speed response under three different control strategies: scalar V/f control, Direct Torque Control (DTC), and DTC combined with Space Vector Modulation (DTC-SVM). While all three methods successfully reach the desired speed of approximately 1400 rpm, they differ in terms of transient performance and stability.
- The V/f control method exhibits the slowest response, with a longer rise time and visible oscillations during the transient period. The settling time is approximately [0.6 s]. This method shows a less stable convergence and is more sensitive to load dynamics.
- DTC significantly improves the system's dynamic response, reaching steady-state quickly with a shorter settling time around [0.3 s]. The transition is sharp and efficient, and the rotor speed stabilizes smoothly without any pronounced speed ripple.
- The DTC-SVM technique offers the best performance, combining the fast response of DTC with even smoother convergence. It reaches the steady-state within [0.4 s] and shows no overshoot or visible oscillations, confirming the effectiveness of the SVM strategy in enhancing control precision.

In conclusion, DTC-SVM demonstrates the most favorable characteristics in terms of speed, accuracy, and stability, making it the most suitable choice for high-performance PV pumping applications.

Parameter	V/f Control	DTC	DTC-SVM
Discharge Water Flow Rate Q (m ³ /s)	0.01158	0.01164	0.0117
Load Torque T_e (Nm)	17.36	17.48	17.61
THD (%)	0.94	6.00	0.54
Output Power (W)	2536	2561	2589
Steady-State Speed Error e_{ss} (%)	2.45	2.17	1.89
Torque Ripple (%)	10.56	14.30	7.88
Settling Time T_s (s)	0.6	0.3	0.4
Sensors Required	None (except MPPT)	2 current sensors	2 current sensors

Table 3.5: Performance Comparison of Control Methods

- Table 3.5 summarizes the key performance indicators of the three control strategies. DTC-SVM outperforms the others in most categories: it achieves the lowest THD (0.54%), lowest speed error (1.89%), and lowest torque ripple (7.88%), while maintaining a fast dynamic response with a settling time of 0.4 s. DTC-SVM also delivers the highest output power of 2589 W and the maximum water flow rate of 0.0117 m³/s, making it the most efficient in terms of pumping performance.
- Although DTC has the fastest response time (0.3 s), it suffers from a higher torque ripple (14.30%) and THD (6%), but it still enables higher performance with an output power of 2561 W and a discharge flow rate of 0.01164 m³/s, both higher than those under V/f control.
- V/f control, on the other hand, shows acceptable results in terms of output power and harmonic content but lags behind in terms of transient behavior and speed accuracy.
- In terms of hardware implementation, V/f control offers the simplest configuration, requiring no sensors aside from the PV-side MPPT. In contrast, both DTC and DTC-SVM require at least two current sensors for torque and flux estimation, increasing system complexity and cost.

Overall, the results clearly highlight the superiority of DTC-SVM for high-performance photovoltaic water pumping applications.

Based on the simulation results and performance indicators, a broader comparison of the control methods is presented in terms of their general advantages, limitations, and implementation aspects.

Category	V/f Control	DTC	DTC-SVM
Advantages	- Simple structure - Easy to implement - Low cost - No feedback sensors - Low switching and sampling frequencies	- Rotor parameter independence - Suitable for IM and PMSM - Simple sensorless operation - No coordinate transformation - No current control loops	- All DTC benefits - Constant switching frequency - Lower torque ripple - Reduced THD - Better power quality - Smoother torque control
Disadvantages	- Poor dynamic response - High steady-state error - Sensitive to load/supply variations - Very poor low-speed control - Not suitable for precision applications	- High torque ripple - No modulator - Bipolar inverter output - Variable switching frequency - High switching losses - High sampling frequency - Limited low-speed precision	- Needs modulator (SVM) - Slightly higher complexity - Requires tuning (DTC + SVM) - Some torque ripple under transients
Complexity & Implementation	Very simple	Moderate complexity	High (due to SVM integration)

Table 3.6: Compact comparison of V/f Control, DTC, and DTC-SVM

Conclusion

This chapter demonstrated the ability of the proposed switched capacitor multilevel inverter topology to efficiently generate boosted multilevel output voltages using a reduced number of components. The integration of Space Vector Modulation (SVM) significantly improved waveform quality and reduced harmonic distortion, with the best current THD reaching 0.54% under DTC-SVM.

A dynamic model of the water pump was developed and integrated into the system, enabling realistic simulation scenarios under variable environmental conditions. Simulations were conducted using three different energy configurations: a DC source, a photovoltaic (PV) source without MPPT, and a PV source with MPPT. The results highlighted the importance of MPPT in maintaining consistent power delivery. Under variable irradiation and temperature, MPPT improved system efficiency and stability, while its absence led to voltage drops and reduced performance.

Three control strategies—V/f control, DTC, and DTC-SVM—were compared. DTC-SVM achieved the best overall performance, combining fast dynamic response, minimal torque ripple (7.88%), and the lowest steady-state speed error (1.89%). It also delivered the highest output power (2589 W) and maximum water flow rate (0.0117 m³/s), confirming its suitability for high-performance PV water pumping.

Altogether, these results validate the proposed inverter topology and control strategies, especially the integration of DTC-SVM and MPPT. The findings establish a solid foundation for the experimental validation discussed in the next chapter.

Chapter 4

Experimental Validation

Introduction

This chapter presents the experimental setup and preliminary results related to the implementation of a photovoltaic-powered pumping system. Due to time and hardware constraints, the full validation of the proposed inverter topology and control strategies could not be completed. However, two key experiments were carried out to assess the behavior of the induction motor when powered by a photovoltaic (PV) source. In both cases, the motor was controlled using a simple V/f (voltage/frequency) control strategy implemented via a potentiometer and an Arduino microcontroller. In the second stage, the pump was coupled to the motor to evaluate the performance of the complete PV–motor–pump system. These tests served as a first step in the hardware validation process, confirming the system’s responsiveness to variations in PV voltage and control inputs.

4.1 Description of the Experimental Set-Up

4.1.1 General Description

The experimental setup reflects a simplified physical implementation of the system modeled in simulation. It includes both the power and control stages.

The **power stage** consists of a two-stage inverter: a Switched Capacitor (SC) DC-DC converter followed by a three-phase inverter, which together supply power to the induction motor. The entire system is powered by a photovoltaic (PV) panel.

The **control stage** features an Arduino Uno that generates control (SVM) signals. A potentiometer allows manual variation of the frequency, enabling a basic implementation of the V/f control method.

For signal monitoring and measurement:

- An **oscilloscope** was used to observe voltage and current waveforms,
- A **multimeter** and **current sensor** were used to record electrical quantities.

4.1.1.1 Power stage

The converter circuit is primarily built from high-power semiconductor devices and passive elements. It enables the transformation of DC energy from the PV source into AC power for the motor load. Recent advances in power electronics have greatly benefited from the development of efficient switching devices such as IGBTs, which are employed in our prototype due to the following characteristics:

- Collector current is controlled via gate voltage, allowing for effective short-circuit protection, active control of $\frac{dv}{dt}$, and overvoltage suppression during turn-off.
- Turn-on is achieved with a +15 V gate voltage, while turn-off occurs at 0 V.

- Only a peak gate current of a few amperes is required during switching transients due to gate-emitter capacitance; no continuous gate current is needed when fully on or off.

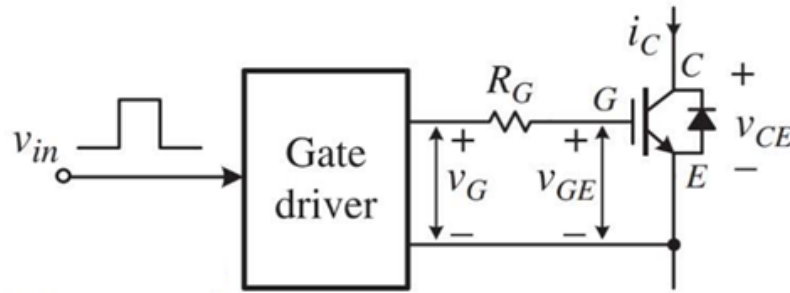


Figure 4.1: IGBT Transistor Characteristics

The proposed topology comprises six IGBTs and three diodes, each equipped with radiators to enhance heat dissipation. Additionally, three capacitors and four fuses are incorporated into the design to fulfill the required functionality and safety considerations. The characteristics of the components used in the prototype are as follows:

1. IGBTs

For the proposed topology, the selected IGBTs have the ability to withstand reverse voltages of Vdc, 2Vdc, and 3Vdc. Specifically, the **Infineon IKW30N60T** IGBTs were chosen for our study, as they can handle voltages up to 600V and a current of 30A [51]. These IGBTs are suitable for the utilized Vdc voltage value in our study. [50]

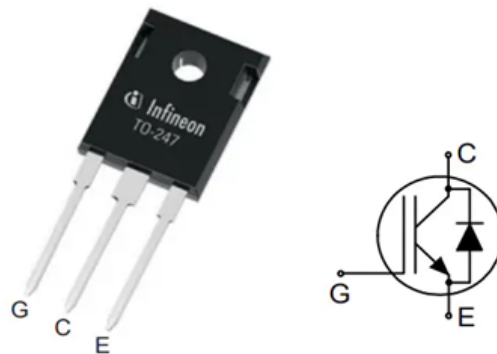


Figure 4.2: IGBT package and its electrical symbol

2. Diodes

In the proposed prototype, each Switched Capacitor (SC) cell is connected to the input voltage V_{dc} via **RURG30100** ultrafast recovery diodes. These components are selected for their high current handling capacity (30 A) and high reverse voltage rating (1000 V), meeting the rapid switching demands of our application.

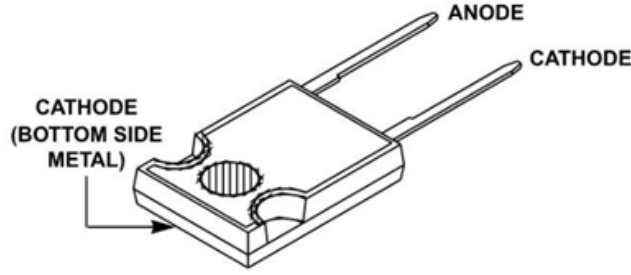


Figure 4.3: Ultrafast RURG30100 Diode

Functionally, the RURG30100 diodes operate as freewheeling elements in coordination with the corresponding switches S_i . When S_i is turned off, the associated diode D_i becomes forward-biased, allowing current flow. Conversely, during the on-state of S_i , D_i is reverse-biased, effectively blocking any unwanted current flow.

3. Radiators

Efficient heat dissipation is crucial to counter the temperature rise resulting from switching and conduction losses in the semiconductor components, as excessive heat can lead to component damage and inverter failure. To tackle this issue, each switch is equipped with a corresponding radiator. In this prototype, **Aavid Thermalloy 6399B** radiators specifically designed for IGBTs and diodes are employed to effectively dissipate heat and prevent overheating.



Figure 4.4: Aavid Thermalloy 6399B radiator

4. Fuses

Utilized as supplementary external protective devices. These fuses act as an additional layer of protection to minimize the potential damage to the switches in the event of overloads or short circuits. In our prototype, three 5A fuses and one 10A are integrated fuse to ensure the preservation of the system and safeguard against excessive current flow or short-circuit situations.

4.1.2 Power-Driver Interface

The power-driver interface, also referred to as the gate drive stage, is essential for controlling the switching states of the power devices. It performs three critical functions:

- Electrical isolation between the control and power stages.
- Amplification and level-shifting of control signals to match the gate drive requirements of the switches, while maintaining ground isolation.
- Analog generation of dead time during IGBT turn-off events.

1. Optocoupler Driver Circuit

The optocoupler provides galvanic isolation between two electronic circuits—one representing the control side and the other the power stage. It consists of an LED and a photodetector. When the input control signal is applied to the LED, it emits infrared light, which is optically transmitted to the photodetector, causing it to conduct.

Optical isolation is particularly advantageous for protecting the control stage from electromagnetic interference originating in the power stage.



Figure 4.5: Integrated Optocoupler-Driver Circuit HCPL-3120

To drive the IGBT gates—which typically require gate voltages between 10 V and 20 V for proper switching dynamics—the driver circuit amplifies and adapts the low-level control signals (3.5–5 V) generated by the controller. This ensures fast and efficient IGBT turn-on and turn-off, minimizing switching losses. The driver also provides a peak gate current of up to 2 A to prevent delay during turn-on.

The HCPL-3120 integrates both the optocoupler and driver functions. Due to its high current capability, it is widely used in IGBT-based applications, where sufficient current must be supplied to rapidly charge the gate capacitance during turn-on[60]

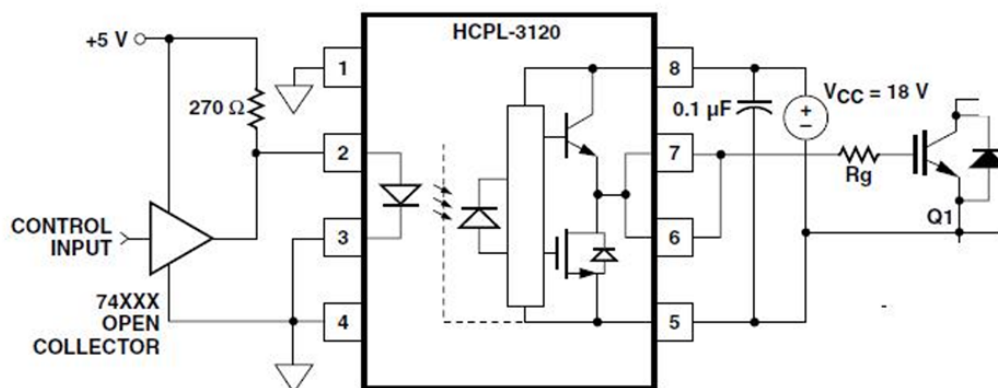


Figure 4.6: Wiring of the HCPL-3120 Optocoupler Driver

2. Regulated Power Supply Circuit

A power supply circuit is used to provide the gate drivers with a stable and time-invariant voltage. This circuit consists of a step-down transformer (220 V/18 V), a single-phase half-wave rectifier to ensure the AC/DC conversion required to obtain the necessary DC voltage, and a capacitive filter to smooth the rectified output. The filter comprises a capacitor C_1 , with a high-value discharge resistor R_1 connected in parallel to ensure automatic discharge when the circuit is turned off.

Additionally, a decoupling capacitor $C_3 \leq \frac{C_1}{100}$ is added in parallel to filter out high-frequency noise that the main electrolytic capacitor cannot attenuate. The regulated output is provided by a voltage regulator of type LM7815, which operates with an input voltage range of 17.7 V to 30 V and delivers a stable 15 V output. [61]

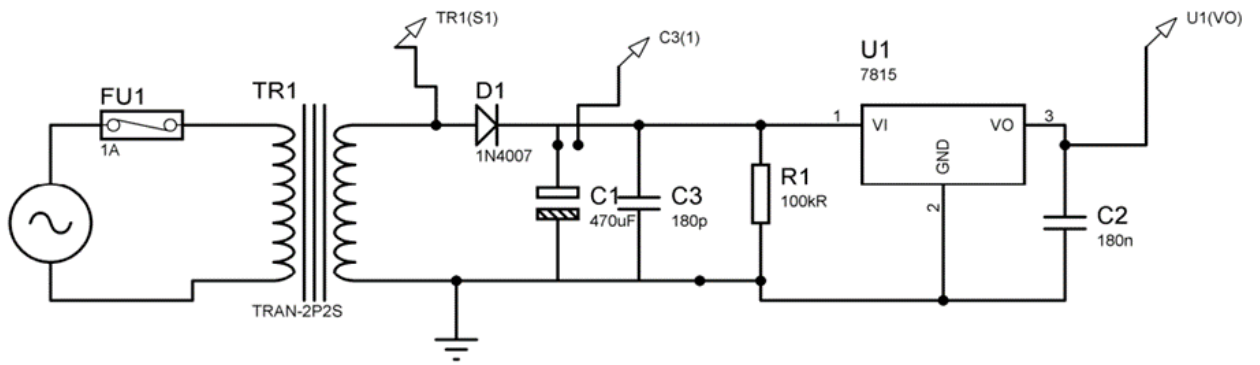


Figure 4.7: Regulated Power Supply Circuit

3. Dead Time Generation

The dead time is generated using an analog RDC (resistor-diode-capacitor) circuit. Since IGBT switches are characterized by a significantly shorter turn-on time compared to their turn-off time, complementary switching commands can lead to short circuits (shoot-through). To prevent this, a dead time is inserted between the turn-off of one IGBT and the turn-on of its complementary switch.

This dead time is introduced by delaying the rising edge of the gate signal while leaving the falling edge unaffected. The rising edge delay is achieved using an RC filter, whereas a diode bypasses the resistor during the falling edge, allowing the capacitor to discharge rapidly. The resulting delay time can be approximated as $t_d \approx RC$.

To ensure adequate protection of the IGBT, the dead time t_d must be greater than the IGBT's turn-off time t_{off} , it is recommended that $t_d = 2$ to $3 \times t_{off}$. [61]

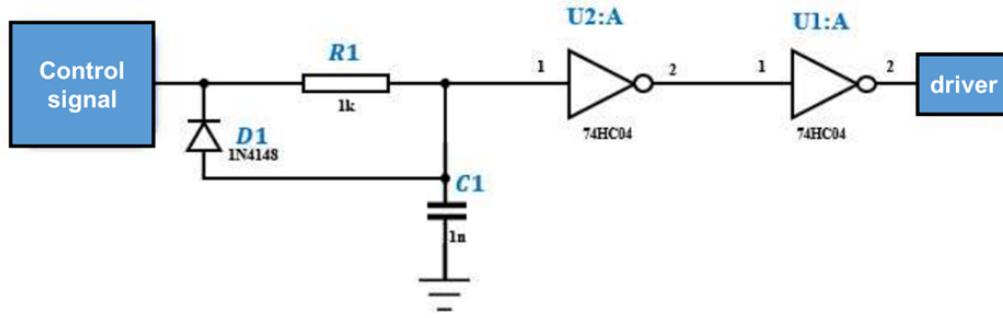


Figure 4.8: Dead Time Generation circuit

To clearly illustrate the physical arrangement, labeled photographs of the setup are presented below (Figure 4.9), with each component assigned a number corresponding to its description in Table 4.1.

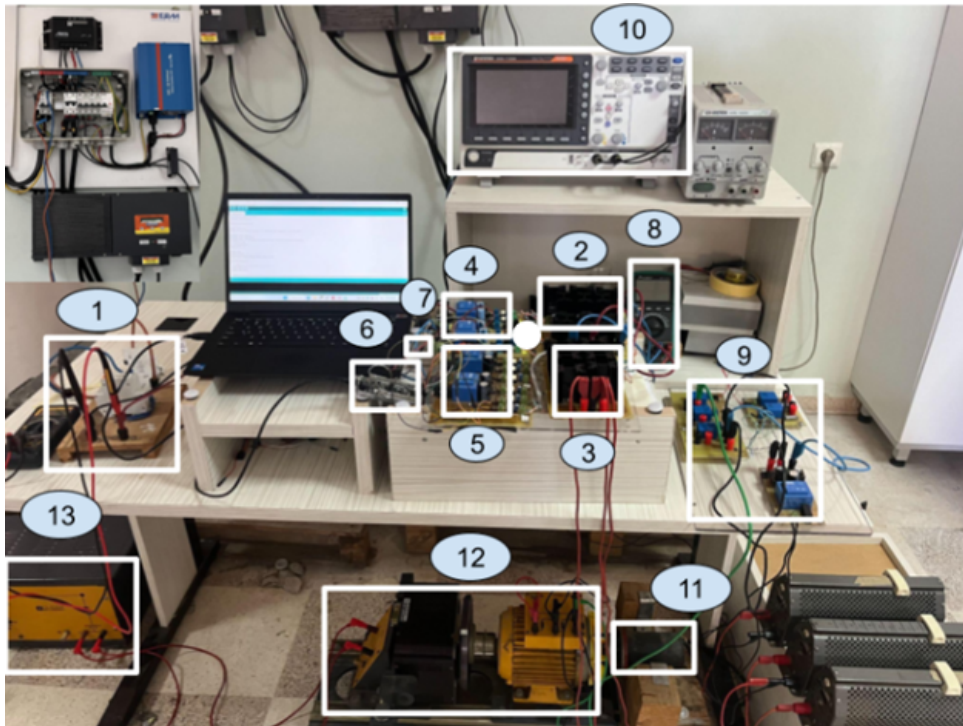


Figure 4.9: Experimental setup used for hardware implementation and testing.

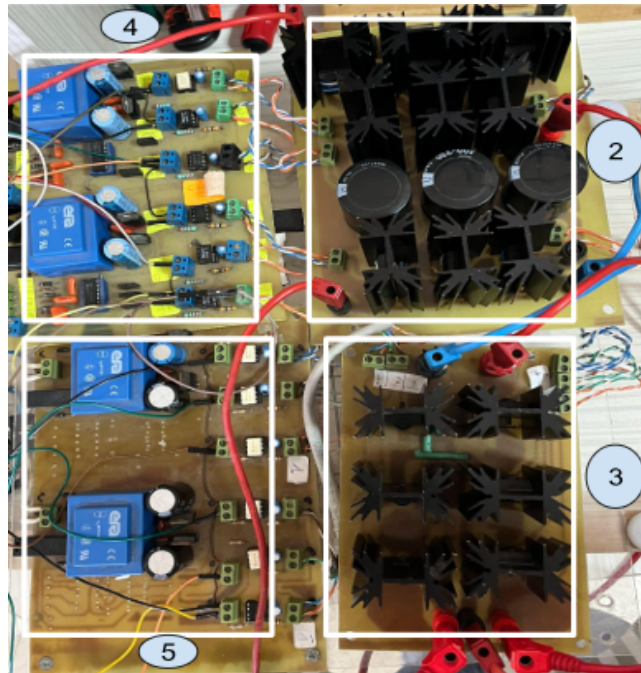


Figure 4.10: Detailed layout of the converter and control circuits



Figure 4.11: Induction motor nameplate

Table 4.1: Summary of Setup Components

No.	Component	Description / Specification
1	PV Source	Photovoltaic panel
2	SC Converter	DC-DC stage for voltage boosting
3	Three-Phase Inverter	Converts boosted DC into three-phase AC
4	SC Control Stage	SVM control of SC converter switches
5	Inverter Control Stage	SVM control of inverter switches
6	Arduino Uno	Generates SVM signals for both stages
7	Potentiometer	Analog input to adjust frequency
8	Multimeter	Voltage and current measurements
9	Current Sensor	Measures current in the system
10	Oscilloscope	Observes electrical waveforms
11	Speed Sensor	Measures motor rotational speed
12	Induction Motor	[motor rating: 380V, 1.1 KW, 50 Hz]
13	Electromagnetic brake	Used as a variable load to absorb mechanical power during testing

Parameter	Value
Nominal Power (P_{nom})	250 Wp
Voltage at P_{max} (V_{mpp})	29.5 V
Current at P_{max} (I_{mpp})	8.48 A
Open-Circuit Voltage (V_{oc})	36.5 V
Short-Circuit Current (I_{sc})	8.84 A
Max System Voltage	1000 V (IEC) / 600 V (UL)
Series Fuse Rating	15 A

Table 4.2: Electrical Characteristics of Solarfabrik PV Module

4.2 Experimental results

This section presents the results of two experimental tests conducted on the PV-powered system. The induction motor was controlled using a basic V/f control implemented via an Arduino Uno and a potentiometer. The purpose of these tests was to validate the functionality of the inverter and the motor's response under different loading conditions.

Test 1: PV Source + Motor with V/f control and electromagnetic brake (load)

In the first test, the motor was initially started under no-load conditions. Once steady operation was achieved, an electromagnetic load was gradually applied to simulate mechanical resistance. The frequency of the inverter output was controlled manually using a potentiometer connected to the Arduino. The potentiometer input was read through a 12-bit ADC, and the frequency was varied from approximately 11 Hz (ADC = 900) to 45.6 Hz (ADC = 3737). The system

was powered by a photovoltaic source delivering a voltage of $V_{PV} = 68.7\text{V}$, and the inverter operated in SVM mode 3, with a modulation index $r = 0.5$.

Input and output current waveforms:

The waveforms reflect the system's behavior across different phases: initial startup, steady-state operation, acceleration and deceleration due to frequency variation, application and removal of the load, and return to steady-state. The observed variations in current confirm the dynamic response of the inverter to both mechanical and control-induced changes.

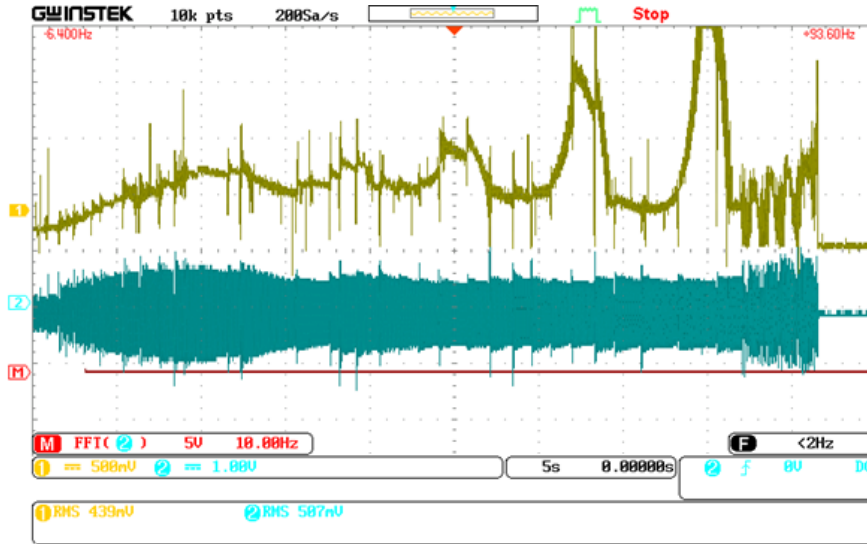


Figure 4.12: Input and output current

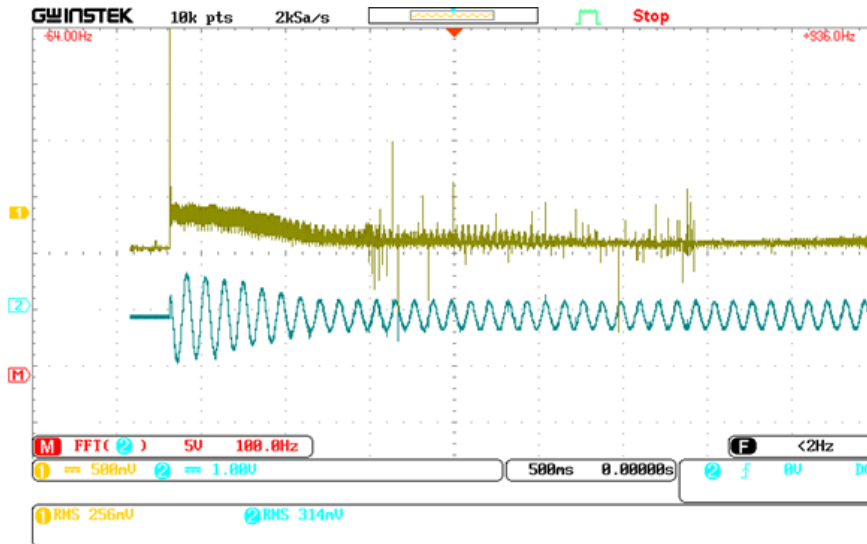


Figure 4.13: Input and output current - zoomed

- The output current is clearly sinusoidal. When analyzing the harmonic spectrum using the measured data, it can be noted that the low frequency harmonics are very low in general $< 2\%$ of the fundamental.
- During the motor's starting phase, we observe a smaller output current waveform, as depicted in Figure 4.13, This reduced current is a direct result of the gradual increase in frequency and voltage characteristic of V/f control, compared to the typical high inrush

current observed during conventional starting methods like Direct-On-Line (DOL). In V/f control, the inverter initiates motor operation at a low frequency and proportionally low voltage, maintaining a constant V/f ratio. This approach prevents the application of full-rated voltage at zero speed — a situation that would otherwise lead to very large inrush currents. As both voltage and frequency are incrementally increased, the motor accelerates smoothly, and the current drawn remains limited throughout the startup process. This gradual ramping is particularly effective during the initial low-speed phase, where the torque demand is highest, yet the current is kept significantly lower than in traditional starting scenarios.

- The high spike in PV current observed during the starting phase is due to Initial High Torque Demand from the Electromagnetic Brake. Under V/f control, although the voltage and frequency are initially low, the torque demand causes a surge in motor current, which directly translates into increased DC (PV) current drawn by the inverter.

DC link voltage waveforms:

The waveforms are shown under no-load and loaded conditions, respectively.

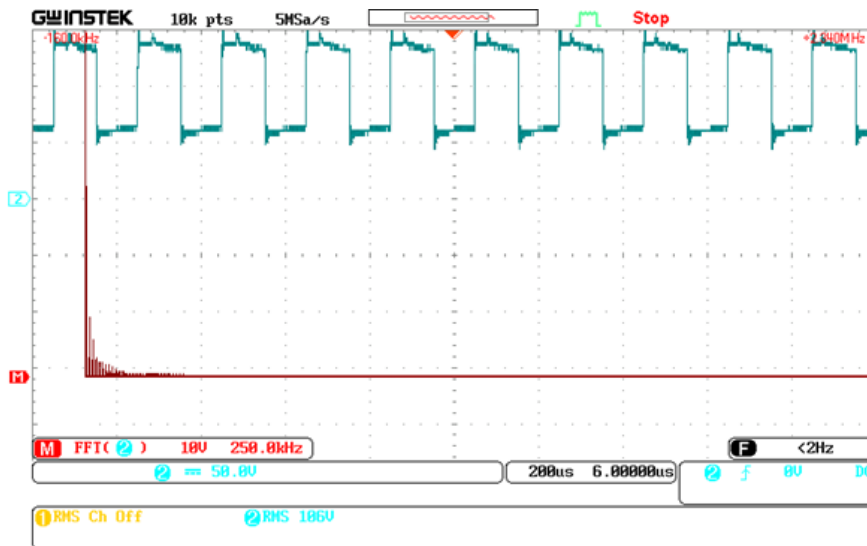


Figure 4.14: DC link voltage - no load

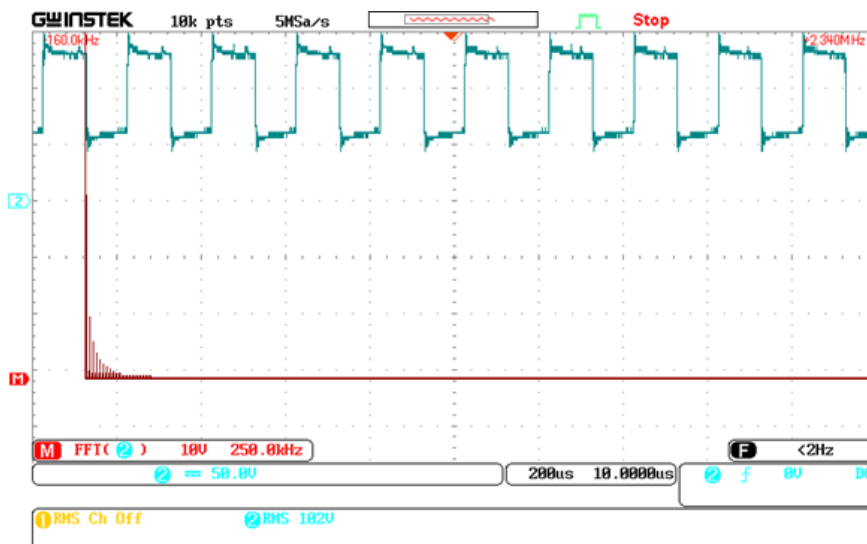


Figure 4.15: DC link voltage under loaded conditions

- The DC link voltage generated by the switched capacitor converter is expected to reach up to four times the PV voltage in Mode 3 operation. However, this theoretical value was not fully achieved in practice, likely due to voltage drops across components, especially during the charging/discharging cycles of the capacitors under high current. The capacitors discharge rapidly in this case. The waveform exhibits two discrete levels— V_{PV} and $(i + 1) \cdot V_{PV}$, which corresponds to $4V_{PV}$ in this case—consistent with the expected behavior of the converter. In terms of measured values, the RMS voltage was approximately 106 V under no-load conditions and decreased slightly to 102 V when the load was applied. This small drop reflects the system's response to increased current demand and inherent losses in the power stage.

Output voltage waveforms:

The waveforms are shown under no-load and loaded conditions, respectively.

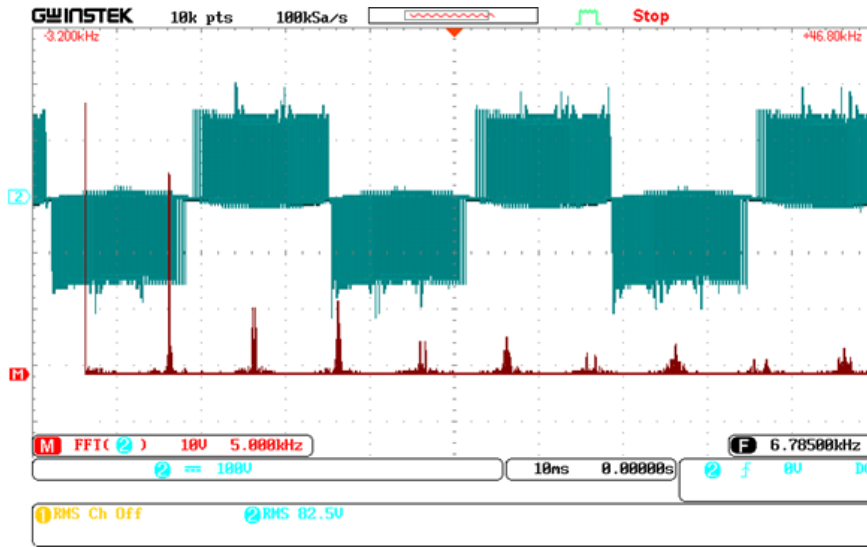


Figure 4.16: Output voltage - no load

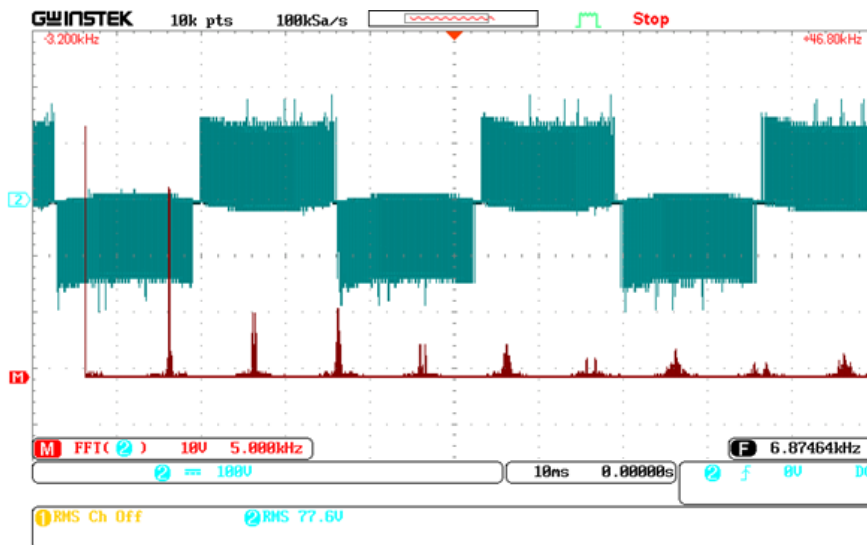


Figure 4.17: Output voltage under loaded conditions

- The output voltage waveform closely resembles the simulation results, with its shape well preserved. The harmonic content remains concentrated around multiples of the

20 kHz switching frequency, while low-frequency components are minimal, confirming the expected spectral behavior. Although the two waveforms (no-load and loaded) appear nearly identical in shape due to the zoomed scale, a slight decrease in the RMS value is observed when the load is applied: from 82.5 V under no-load conditions to 77.6 V under load. This drop reflects the increased power demand and the limitations of the open-loop V/f control and PV source in fully compensating for voltage drops under load.

Speed waveform:

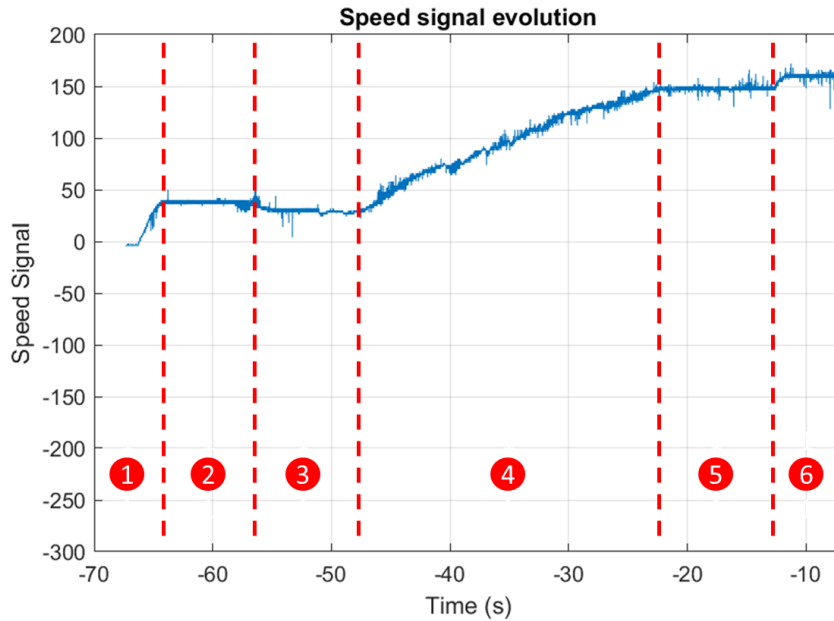


Figure 4.18: Speed waveform

The different numbered regions in Figure 4.18 illustrates the evolution of the motor speed signal under different operating conditions:

1. **Startup:** The motor accelerates from zero speed, indicating the initial startup phase.
 2. **First steady state:** The motor reaches and maintains a stable speed.
 3. **Load application:** A sudden drop in speed is observed due to the application of load torque.
 4. **Acceleration:** The reference frequency is gradually increased using a potentiometer, leading to a progressive speed increase.
 5. **Second steady state:** The motor stabilizes at a new constant speed under loaded conditions.
 6. **Unloading:** The load is removed, causing a brief overshoot before the speed stabilizes again.
- The motor speed waveform illustrates the mechanical behavior during the same test. A slight drop in speed is observed when the electromagnetic load is applied. As the frequency is increased via the potentiometer, the motor accelerates accordingly. This confirms that the system responds effectively to both frequency input and load variations under the implemented control strategy.

Test 2: PV Source + Motor with V/f control and Pump Load

In the second test, the electromagnetic load was removed and replaced by a pump mechanically coupled to the motor. The same V/f control method was maintained. The goal was to observe the system's ability to drive a real mechanical load. Similar to the previous test, waveforms and setup images were recorded and are presented below, followed by an interpretation of the pump-driven operation.

- Case 1:

The system was powered by a photovoltaic source (one solar panel) delivering a voltage of $V_{PV} = 68.7\text{V}$, and the inverter operated in SVM mode 3, with a modulation index $r = 0.5$.

V_{pv} (V)	I_{pv} (A)	f (Hz)
68.7	6.2	50

Table 4.3: Photovoltaic voltage, current, and frequency values

Input and output current waveforms:



Figure 4.19: Input and output current

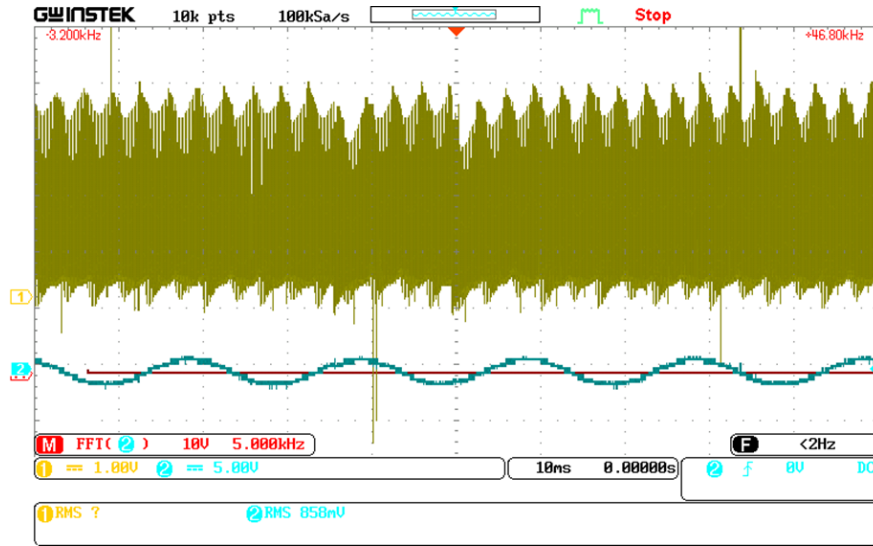


Figure 4.20: Input and output current (zoomed in)

Output voltage waveform:

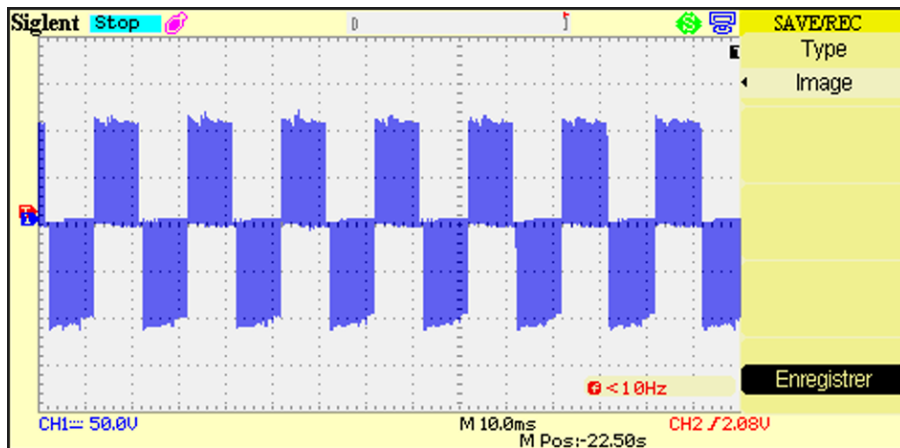


Figure 4.21: Output voltage

- Case 2:

The system was powered by a photovoltaic source delivering a voltage of $V_{PV} = 132$ V, and the inverter operated in SVM mode 3, with a modulation index $r = 0.5$.

Panel type	Number of series modules	Number of parallel strings
Solarfabrik	4	2

Table 4.4: The parameters of the PV generator

V_{pv} (V)	I_{pv} (A)	f (Hz)
132	9.2	50

Table 4.5: Photovoltaic voltage, current, and frequency values

Input and output current waveforms:

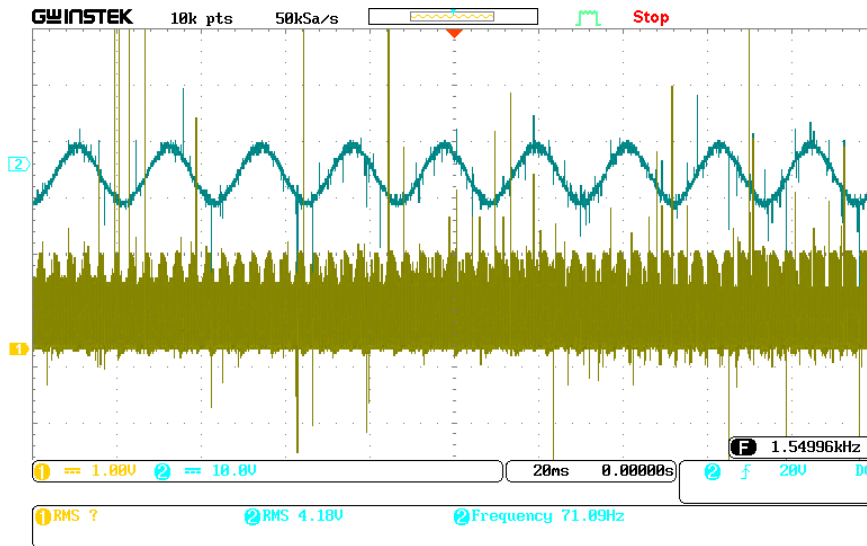


Figure 4.22: Input and output current (lower frequency)

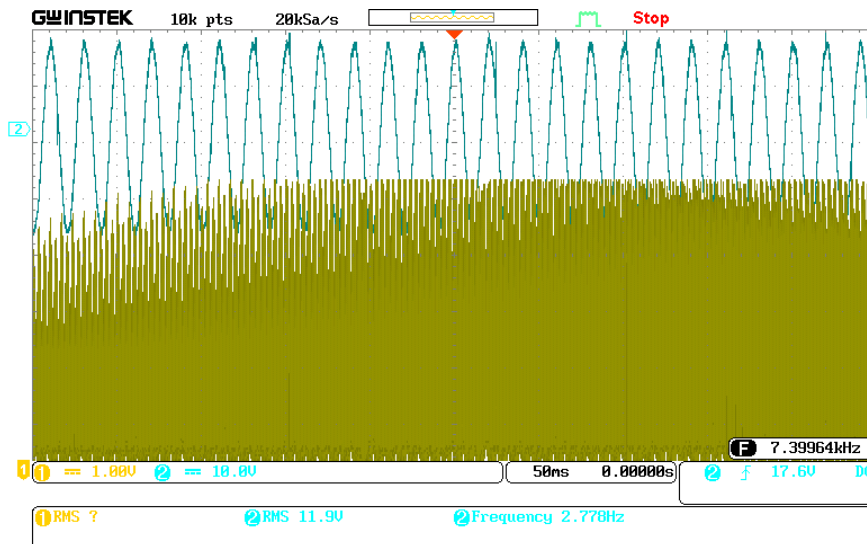


Figure 4.23: Input and output current (higher frequency)

Output voltage waveform:

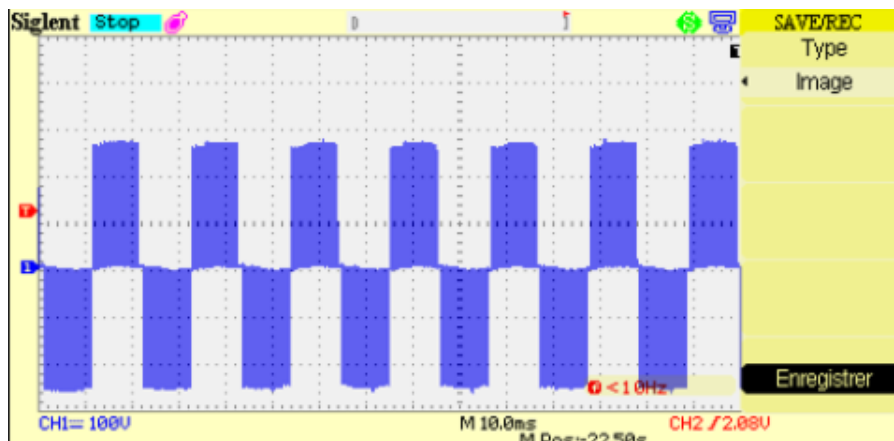


Figure 4.24: Output voltage

Interpretations

- Similar to the simulation results, the output current exhibits a clearly sinusoidal waveform, with a harmonic spectrum that remains clean and free of significant distortion.
- The output voltage waveform U_{ab} reflects the switching behavior of the inverter under V/f control. While it does not exhibit a clearly defined multilevel structure (as would be seen in the phase voltages), it still indicates that the inverter is generating the appropriate voltage pattern for motor operation.
- In Test 2, with increased frequency, the input PV current is increased up to 9.2amps. Increasing the output frequency of the inverter results in higher motor speed, which increases mechanical load (especially if a pump is connected), and this in turn leads to a higher power demand from the motor. Since the inverter is powered by a PV source, the system draws more current from the PV panel to meet that demand.
- In Test 2, using two PV panels instead of one increased the power supplied to the system. This allowed the motor to operate at a higher speed and deliver greater torque, which led to a noticeable improvement in the water flow rate. Despite the pump operating under suboptimal voltage conditions, the system still delivered a peak power of 1.2 kW, demonstrating satisfactory performance.

Conclusion

This chapter presented the hardware implementation and preliminary experimental validation of the proposed switched capacitor inverter (SCI) topology applied to a photovoltaic water pumping system. Despite time and hardware limitations that prevented full validation, the conducted tests provided valuable insight into real-world system behavior.

In the first experimental scenario, the inverter was used to drive an induction motor directly from a PV source. The system successfully initiated motor startup without load, confirming proper voltage conversion and switch operation. The V/f control strategy enabled visible speed variation through a potentiometer, and measured signals confirmed expected inverter behavior.

The second test involved a motor-pump assembly under light mechanical load, with a two-stage inverter structure controlled via SVM. The output voltage waveform was clearly multilevel, and the current remained sinusoidal. Experimental FFT results showed harmonics consistent with simulation, and speed measurements closely matched theoretical expectations. Although voltage boosting did not reach the full simulated $4 \times V_{pv}$ level—likely due to internal drops and losses—the system maintained stable operation.

Overall, the experimental results confirmed the feasibility of the proposed SCI topology and demonstrated successful initial validation of control and power stages. These findings pave the way for future work focused on closed-loop implementation, full MPPT integration, and further performance optimization under real environmental conditions.

General Conclusion

This thesis presented the modeling, control, simulation, and experimental validation of a photovoltaic (PV)-powered water pumping system based on a switched capacitor multilevel inverter (SCMLI). The main objective was to develop a compact and efficient power conversion system adapted for remote and off-grid environments, where sustainability and simplicity are key.

The first chapter provided a theoretical foundation, reviewing both photovoltaic technologies and multilevel inverter topologies. It introduced switched capacitor inverters as a promising alternative to conventional structures due to their ability to self-boost voltage levels without magnetic components, while maintaining a reduced component count. The chapter also detailed the principles of PV generation, the impact of environmental conditions, and the motivation behind applying SCMLI to solar pumping systems.

The second chapter focused on the detailed presentation of the proposed three-phase SCMLI topology and the modeling of the hydraulic subsystem. The inverter's switching modes and integration with Space Vector Modulation (SVM) were described to support multilevel voltage generation with improved waveform quality. In parallel, the pump was modeled using performance data, and the hydraulic circuit was built to represent the mechanical load. This modeling formed the structural basis for the simulations and control strategies implemented later in the study.

The third chapter addressed the implementation of three control strategies—V/f, DTC, and DTC-SVM—and their application to the full system simulation. Multiple case studies were carried out using a constant DC source, a PV source without MPPT, and a PV source with MPPT, under both fixed and variable environmental conditions. Simulation results demonstrated that the DTC-SVM method offered the best compromise between dynamic performance, torque quality, and voltage regulation, especially in the presence of irradiance and temperature fluctuations.

The fourth and final chapter presented the experimental setup and validation. Despite time and hardware constraints, the key functionalities of the inverter were successfully tested. The system was able to drive an induction motor and pump load using PV power and basic V/f control. Waveform observations and electrical measurements confirmed the proper functioning of the hardware, thereby validating the relevance of the proposed topology for real-world deployment.

In conclusion, this work confirms the viability of using a switched capacitor inverter for PV-powered water pumping applications. The proposed system combines structural simplicity, self-voltage boosting, and effective control strategies to deliver reliable operation under diverse

conditions. Future work could focus on implementing real-time MPPT algorithms, integrating energy storage, and developing embedded control solutions to move toward a fully autonomous and field-ready system.

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