

RECENT INNOVATIONS IN ELECTRICAL, ELECTRONICS AND COMMUNICATIONS



Editör: Bilal TÜTÜNCÜ



BİDGE Yayınları

**Recent Innovations in Electrical, Electronics and
Communications**

Editor: BİLAL TÛTÛNCÛ

ISBN: 978-625-8995-20-6

1st Edition

Page Layout By: Gzde YÛCEL

Publication Date: 2026-03-25

BİDGE Yayınları

All rights reserved. No part of this work may be reproduced in any form or by any means, except for brief quotations for promotional purposes with proper source attribution, without the written permission of the publisher and the editor.

Certificate No: 71374

All rights reserved © BİDGE Yayınları

www.bidgeyayinlari.com.tr - bidgeyayinlari@gmail.com

Krc Bilişim Ticaret ve Organizasyon Ltd. Őti.

Gzeltepe Mahallesi Abidin Daver Sokak Sefer Apartmanı No: 7/9 Çankaya /
Ankara



PREFACE

This book aims to provide a comprehensive overview of recent innovations and advancements in the fields of electrical, electronics, and communications engineering. In the context of rapid technological evolution, these disciplines have become fundamental in addressing complex challenges and enabling transformative solutions across various sectors.

The chapters included in this volume present both theoretical frameworks and practical applications, reflecting current research trends and technological progress. By integrating diverse perspectives, this work seeks to contribute to the existing body of knowledge and support further academic and industrial developments.

It is anticipated that this book will serve as a valuable reference for researchers, scholars, and practitioners, and will foster continued innovation in electrical, electronics, and communications technologies.

Assoc. Prof. Dr. Bilal TÜTÜNCÜ

CONTENTS

DIGITAL TWINS FOR RENEWABLE ENERGY AND POWER ELECTRONICS: TOWARD SELF-AWARE ENERGY SYSTEMS	1
<i>SEYFULLAH DEDEOĞLU</i>	
ÇBAG TABANLI RÜZGÂR ÇİFTLİĞİNDE ALT-SENKRON REZONANS DURUMLARININ İNCELENMESİ İÇİN BULANIK MANTIK TABANLI TCSC MODELİNİN GELİŞTİRİLMESİ	20
<i>MEHMET KENAN DÖŞOĞLU</i>	
ROBUST DC LINK VOLTAGE CONTROL IN PV INVERTERS: A SLIDING MODE APPROACH	40
<i>ZEYNEP BALA DURANAY, İSMAİL ANIL AVCI, HANİFİ GÜLDEMİR</i>	
INFORMATION ABOUT BRUSHLESS DC (BLDC) MOTORS	64
<i>İSHAK PARLAR</i>	

CHAPTER 1

DIGITAL TWINS FOR RENEWABLE ENERGY AND POWER ELECTRONICS: TOWARD SELF- AWARE ENERGY SYSTEMS

SEYFULLAH DEDEOĞLU¹

Introduction

Energy systems are entering an era in which decarbonization, power-electronic conversion, and pervasive sensing are evolving at the same pace. Under these conditions, conventional monitoring dashboards are no longer sufficient. Operators need digital environments that do not merely display measurements but also interpret asset behavior, anticipate degradation, and support timely decisions. The digital twin has therefore moved from its aerospace and manufacturing roots into the core of energy engineering, where it is increasingly used to connect field data, engineering models, and operational intelligence in a single closed loop (Glaessgen & Stargel, 2012; Grieves & Vickers, 2017; Tao et al., 2019; Fuller et al., 2020).

A digital twin is best understood as a living representation of a physical asset or system that remains synchronized with its real counterpart through data streams, model updating, and decision

¹ Assistant Professor, Hitit University, Department of Electrical and Electronics Engineering, ORCID: 0000-0001-7969-011X

feedback. This view is more demanding than the use of a static simulation model, because it requires continuity, traceability, and purposeful interaction with operation and maintenance processes. The distinction between a digital model, a digital shadow, and a true digital twin is particularly useful in practice: only the last implies bidirectional coupling that allows the digital entity to influence how the physical system is managed (Kritzinger et al., 2018; Rasheed et al., 2020).

Renewable generation and power-electronic conversion are especially suitable domains for digital twins because they combine environmental variability with fast dynamics, component ageing, and distributed control. A photovoltaic plant is shaped by irradiance, temperature, mismatch, and inverter behavior; a wind turbine is governed by turbulent loading, aeroelastic effects, and drivetrain health; and a converter-dominated microgrid must coordinate numerous devices with limited physical inertia. In all of these cases, operational value depends on the ability to merge engineering knowledge with real-time measurements and contextual information such as weather, market signals, and maintenance records (Onile et al., 2021; Chen et al., 2023; Song et al., 2023).

This chapter examines how digital twin thinking can be translated into technically credible and operationally useful solutions for renewable energy systems and power electronics. The discussion begins with conceptual foundations, then moves toward reference architectures, application scenarios, implementation challenges, and future research directions. Throughout the chapter, emphasis is placed on fit-for-purpose modeling, lifecycle value, and the role of digital twins as decision instruments rather than as fashionable labels.

Conceptual Foundations of the Digital Twin

The intellectual foundations of the digital twin were established around the idea that complex assets should be accompanied by high-value digital counterparts throughout their lifecycle. Early formulations emphasized persistent digital representation, simulation-supported reasoning, and the possibility of reducing uncertainty in the management of safety-critical systems (Glaessgen & Stargel, 2012; Boschert & Rosen, 2016; Grieves & Vickers, 2017). Later literature refined the concept by clarifying its informational structure, its synchronization mechanisms, and its difference from ordinary design models or off-line simulators (Kritzinger et al., 2018; Tao et al., 2019).

For engineering practice, the most important conceptual lesson is that a digital twin should be designed for a clearly defined operational purpose. A twin intended for fault diagnosis in a grid-connected inverter does not require the same model structure, update rate, or uncertainty treatment as a twin used for annual maintenance planning of a wind farm. In other words, fidelity is not an absolute virtue. The right twin is the one whose physical assumptions, data interfaces, and computational burden are aligned with the service it must deliver. This fit-for-purpose perspective also prevents the common mistake of equating a digital twin with a very detailed but operationally disconnected simulation package (Fuller et al., 2020; Rasheed et al., 2020).

A second foundational idea is that digital twins create value across the lifecycle rather than at a single operational instant. The same twin framework can inform design choices, commissioning tests, control calibration, anomaly detection, maintenance prioritization, and retrofit decisions. In the energy domain, this lifecycle continuity is particularly attractive because plants and converters operate for long periods under changing duty cycles, tariff structures, and environmental conditions. The more effectively a

digital twin captures this evolving history, the more useful it becomes for asset intelligence, service planning, and strategic reinvestment (Tao et al., 2019; Do Amaral et al., 2023).

Table 1. Widely accepted digital twin milestones and their significance for energy systems

Study	Core contribution	Relevance to renewable energy and power electronics
Glaessgen & Stargel (2012)	Introduced the digital twin paradigm for safety-critical vehicles and lifecycle-oriented reasoning.	Established the idea of continuously informed digital counterparts for mission-critical assets and operations.
Boschert & Rosen (2016)	Emphasized the simulation dimension of the digital twin across lifecycle phases.	Supports what-if analysis, commissioning studies, and scenario testing for energy conversion systems.
Grieves & Vickers (2017)	Positioned the twin as a mechanism for reducing undesirable emergent behavior in complex systems.	Highly relevant to converter-dominated plants where local interactions can create system-level consequences.
Kritzinger et al. (2018)	Distinguished digital model, digital shadow, and digital twin.	Provides a practical taxonomy for defining the maturity of energy-sector deployments.
Tao et al. (2019)	Presented a state-of-the-art industrial view of digital twin integration.	Clarifies the need to couple models, data, and service functions in operational environments.
Fuller et al. (2020)	Reviewed enabling technologies, challenges, and open research questions.	Offers an implementation roadmap for data, communication, analytics, and governance decisions.

Why Renewable Energy and Power Electronics Need Digital Twins

Renewable energy assets are not only geographically distributed; they are also physically heterogeneous and environmentally exposed. Traditional supervisory systems report electrical variables and alarms, yet they often provide limited insight

into why a performance deviation occurred or which intervention would be most effective. Digital twins address this limitation by linking measured outputs to causal structures, whether these are device-level electrical models, aero-mechanical models, or hybrid estimators that combine first-principles reasoning with historical data. This is why digital twin research in energy has expanded from isolated case studies to broader reviews covering wind, solar, and integrated energy services (De Kooning et al., 2021; Onile et al., 2021; Do Amaral et al., 2023).

Power electronics are an equally compelling application field because they operate at high speed, sit at the interface between sources and loads, and accumulate stress in ways that are not always directly observable. Semiconductor junction temperature, capacitor ageing, solder fatigue, and magnetic losses all influence converter reliability, but many of these internal states must be inferred rather than directly measured. A digital twin can fuse electrical, thermal, and control information to estimate hidden states, interpret health indicators, and support condition-aware operation. Recent work on converter twins has shown that this approach can move beyond off-line analysis toward practical monitoring and control functions (Peng et al., 2021; Chen et al., 2023; Lei et al., 2023).

At the system level, the growing share of inverter-based resources is reshaping the structure of modern power systems. Coordination now depends increasingly on software-defined control, distributed optimization, and cyber-physical observability. In such settings, a digital twin is valuable not only because it improves local asset visibility but also because it creates a coherent decision layer spanning devices, microgrids, and supervisory platforms. This broader role is particularly evident in digital twin work on microgrids and future power systems, where resilience, economic dispatch, and multi-asset coordination are treated as interconnected rather than separate design problems (Bazmohammadi et al., 2022;

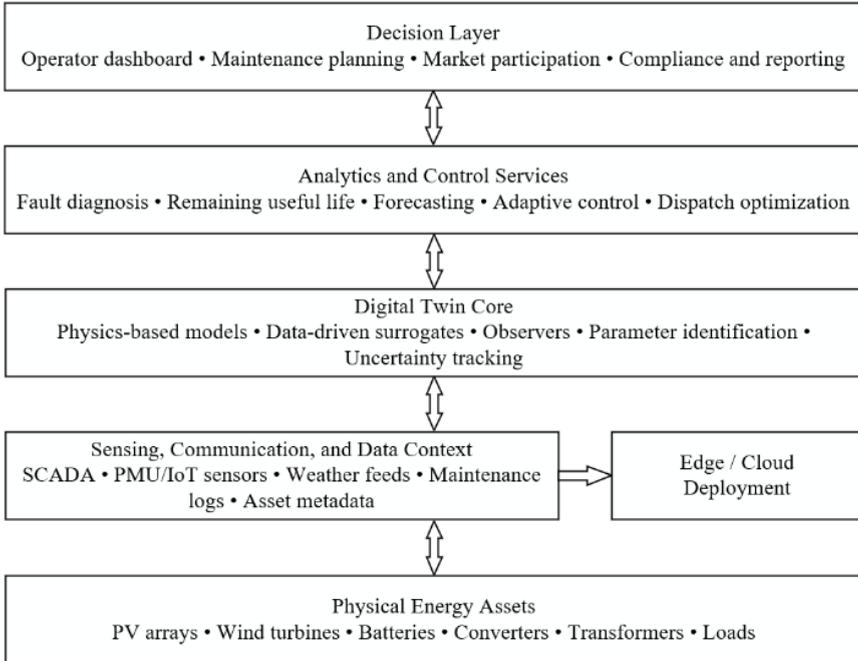
Song et al., 2023). Table 1 summarizes the contributions of some key papers to emphasize the importance of digital twins in energy studies.

Reference Architecture and Enabling Technologies

A practical digital twin for renewable energy or power-electronic conversion can be understood as a layered structure as given in Figure 1. At the base lies the physical system: photovoltaic arrays, wind turbines, storage units, converters, transformers, or networked loads. Above it sits the data-acquisition layer, where sensors, supervisory control and data acquisition streams, weather services, maintenance logs, and configuration metadata are collected and organized. The digital twin core then combines this information with physical models, reduced-order representations, and data-driven estimators. On top of the core, analytics and control services transform synchronized information into diagnosis, forecasting, control recommendations, and maintenance actions (Fuller et al., 2020; Chen et al., 2023).

The synchronization mechanism is central to the architecture. A useful twin does not refresh all variables at the same rate or with the same confidence. High-speed converter control may require sub-second updates for selected states, whereas maintenance-oriented twins can operate effectively at slower intervals using batch data. Similarly, some variables are directly measured, others are estimated, and still others are inferred with uncertainty bounds. A mature architecture therefore distinguishes between fast operational synchronization, slower parameter calibration, and event-based updating triggered by faults, weather transitions, or maintenance actions. This temporal selectivity is essential for keeping the twin both computationally tractable and operationally meaningful (Rasheed et al., 2020; De Kooning et al., 2021; Lei et al., 2023).

Figure 1. A layered digital twin architecture for renewable energy and power-electronic assets



Source: Prepared by the author based on Glaessgen and Stargel (2012), Kritzinger et al. (2018), Fuller et al. (2020), and Chen et al. (2023).

Modeling choices are equally important. Purely physics-based twins remain attractive because they preserve interpretability and can extrapolate more safely outside the observed data range. Yet energy systems often operate under nonlinear, time-varying, and partially observed conditions that make purely mechanistic modeling insufficient. For this reason, many of the most promising energy-oriented twins are hybrid in nature. They use first-principles structures to encode conservation laws, switching logic, or electro-thermal dynamics, while data-driven elements compensate for unmodeled losses, parameter drift, or complex environmental effects. This hybridization is increasingly visible in both survey

literature and recent case studies on power conversion systems (Tao et al., 2019; Chen et al., 2023; Lei et al., 2023).

Deployment strategy is the final enabling decision. Edge-hosted twins are attractive when latency is critical, for example in converter monitoring, protective actions, or local microgrid control. Cloud-hosted twins are more suitable for fleet analytics, historical learning, and computationally intensive scenario evaluation. In practice, the most robust solutions are neither exclusively edge nor exclusively cloud based. They distribute functions according to latency, bandwidth, cybersecurity, and ownership constraints, while preserving a coherent semantic model across the full cyber-physical stack (Onile et al., 2021; Song et al., 2023).

Applications in Renewable Generation, Storage, and Conversion

In photovoltaic systems, digital twins can be used to separate environmental variability from technical underperformance. This makes them especially valuable for identifying mismatch, soiling, partial shading, sensor drift, and inverter-related losses without confusing these issues with ordinary weather-driven changes in output. When the twin is coupled with irradiance and temperature forecasts, it can also support day-ahead expectations, alarm rationalization, and maintenance prioritization. The result is a more diagnostic and less reactive mode of plant supervision, which is one of the reasons energy digital twin reviews place solar applications among the most promising near-term use cases (Onile et al., 2021; Do Amaral et al., 2023).

Wind energy conversion systems benefit from digital twins in a somewhat different way. Here, the central challenge is not only performance assessment but also structural and drivetrain loading across highly variable operating conditions. A wind turbine twin may therefore incorporate aeroelastic models, drivetrain dynamics,

vibration signatures, supervisory data, and environmental information at different fidelity levels. The literature has repeatedly shown that the main engineering question is not whether a wind twin should be built, but how much fidelity is justified for a given decision horizon, especially when computational load must remain compatible with practical deployment (De Kooning et al., 2021).

Battery-integrated converters and standalone power-electronic stages are even more tightly coupled to digital twin thinking because many of their critical states are internal. State of charge, state of health, junction temperature, parasitic losses, and health indicators cannot always be measured directly, yet they strongly affect efficiency, safety, and remaining useful life. For this reason, digital twins in power electronics are increasingly oriented toward state estimation, adaptive calibration, and control co-design. Studies on DC-DC converters, for example, demonstrate that a twin can estimate health indicators or support monitoring and control functions while remaining close enough to the physical converter to be operationally useful rather than merely descriptive (Peng et al., 2021; Chen et al., 2023; Lei et al., 2023).

Table 2. Representative digital twin targets in renewable energy and power electronics

Domain	Twin objective	Typical model/data basis	Operational value
PV plant	Performance diagnosis and forecast-aware supervision	Equivalent-circuit models, weather data, inverter telemetry	Yield improvement and better alarm interpretation
Wind turbine	Load monitoring and drivetrain prognostics	Aeroelastic models, SCADA streams, vibration data	Maintenance planning and availability improvement
Battery-converter system	State/health estimation and adaptive control	Electro-thermal models, current-voltage-temperature histories	Life extension, safer loading, and lower downtime

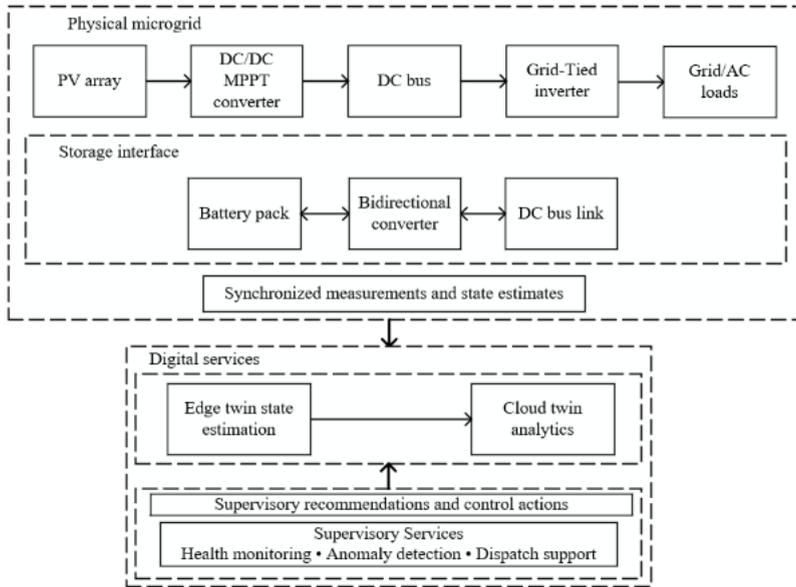
Microgrid / DER fleet	Coordination, resilience, and condition-aware dispatch	Network models, device twins, market/weather context	Stable operation and economically informed control
-----------------------	--	--	--

Source: Compiled by the author based on De Kooning et al. (2021), Onile et al. (2021), Peng et al. (2021), Bazmohammadi et al. (2022), Chen et al. (2023), Do Amaral et al. (2023), Lei et al. (2023), and Song et al. (2023).

The most ambitious applications move beyond individual assets toward microgrids and wider power-system services. In these settings, the digital twin is no longer just an asset-specific model; it becomes a compositional environment in which multiple device twins interact with network, market, and control layers. Such arrangements support resilience studies, coordinated control of distributed energy resources, condition-aware dispatch, and the testing of operating strategies before they are pushed to the field. As digital twin concepts mature, this multi-scale orchestration function is likely to become one of their defining contributions to converter-dominated energy systems as explained in Table 2 (Bazmohammadi et al., 2022; Song et al., 2023).

An important practical consequence of these application patterns is that digital twins increasingly serve human decision-makers rather than replacing them. Their best implementations enhance operator awareness, compress diagnosis time, and help maintenance teams distinguish urgent interventions from noise. In this sense, the twin is most valuable when it makes the physical system more legible: it converts scattered sensor streams into an engineering narrative that supports action under uncertainty (Fuller et al., 2020). An example application of digital twin for a DC microgrid is provided in Figure 2.

Figure 2. A cyber-physical digital twin configuration for a renewable-integrated DC microgrid



Source: Prepared by the author based on Bazmohammadi et al. (2022), Chen et al. (2023), and Song et al. (2023).

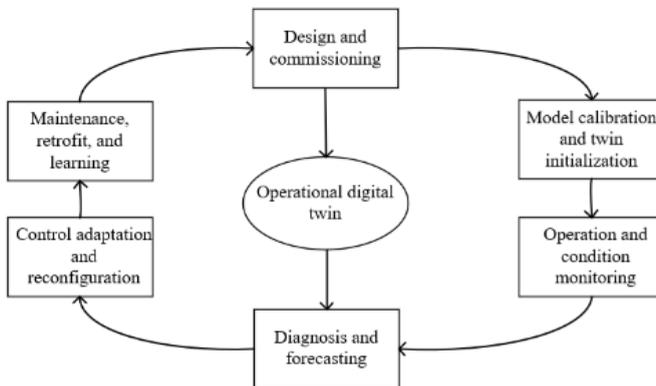
Operational Analytics: Estimation, Diagnosis, and Control

The operational value of a digital twin lies in its ability to transform raw data into interpretable states, parameters, and predictions as illustrated in Figure 3. Virtual sensing is a good example. Many variables that matter in renewable energy and power electronics are either expensive to measure or impossible to observe directly during normal operation. By embedding physics-based relations and continuously adapting parameters with live data, a digital twin can estimate hidden quantities such as thermal stress, loss coefficients, or health indicators with far greater context than a purely statistical alarm system. The quality of such estimates depends not only on model accuracy but also on uncertainty

treatment, observability, and update discipline (Rasheed et al., 2020; Peng et al., 2021; Lei et al., 2023).

Diagnosis and prediction form the next analytical layer. Once the twin can distinguish normal variability from meaningful deviation, it becomes possible to identify the likely origin of a fault, estimate the severity of degradation, and forecast the consequences of delayed intervention. In energy assets, this is particularly important because maintenance windows are constrained by weather, crew availability, and market conditions. A twin that links component condition to operational planning can therefore create value beyond maintenance itself: it supports better dispatch decisions, more informed spare-parts strategies, and a clearer understanding of risk exposure over the asset lifecycle (Tao et al., 2019; Fuller et al., 2020; De Kooning et al., 2021).

Figure 3. Closed-loop lifecycle services enabled by an operational digital twin



Source: Prepared by the author based on Tao et al. (2019), Fuller et al. (2020), Rasheed et al. (2020), and Do Amaral et al. (2023).

Control is the most advanced and demanding use of the digital twin. Here, the twin is not only an observer but also a companion model that helps evaluate or tune decisions before they are enacted. In converter-heavy systems, this can mean adaptive

parameter updates, model-based supervisory control, safe operating envelope assessment, or the coordination of multiple distributed resources. The practical lesson from recent power-electronic studies is that control-oriented twins must remain computationally disciplined. Reduced-order or surrogate representations are often more useful than maximal-detail simulations when the objective is robust, real-time decision support (Chen et al., 2023; Lei et al., 2023; Bazmohammadi et al., 2022).

Implementation Challenges and Standardization Needs

Despite rapid progress, digital twin deployment in energy engineering still faces several obstacles. The first is data quality. Measurements may be noisy, missing, time-misaligned, or poorly contextualized. Asset metadata may be incomplete, operating modes may be inconsistently labeled, and maintenance actions may be recorded in free text rather than in structured formats. Under such conditions, even a sophisticated twin will struggle to maintain trustworthy synchronization. This is why implementation success depends as much on data governance and instrumentation discipline as on algorithmic sophistication (Fuller et al., 2020; Do Amaral et al., 2023).

A second challenge is model drift. Renewable assets and converters do not behave identically across seasons, loading histories, firmware revisions, or ageing trajectories. Parameters shift, control modes change, and failure precursors emerge gradually. If the twin is not recalibrated and validated continuously, it may appear precise while slowly losing physical credibility. Robust digital twin practice therefore requires systematic treatment of uncertainty, version control for model updates, and explicit validation protocols for different operating regimes rather than a single one-time accuracy report (Rasheed et al., 2020; De Kooning et al., 2021).

Interoperability and cybersecurity are equally critical. A renewable plant often involves equipment from multiple vendors, each with different data semantics, communication interfaces, and protection constraints. Building a useful digital twin across such boundaries requires more than raw connectivity; it requires stable information models, transparent ownership rules, and secure communication paths. This challenge becomes even more serious when twins participate in supervisory control or market-facing optimization, because the consequences of corrupted data or compromised recommendations extend beyond a single device (Onile et al., 2021; Song et al., 2023).

Finally, the economics of digital twins must be stated clearly. Not every asset needs a full-scale, continuously synchronized, high-fidelity twin. In many cases, value emerges from a narrower service such as fault localization, health estimation, or maintenance prioritization. A strong deployment strategy therefore begins by defining the decision to be improved, then works backward to the minimum viable sensing, modeling, and computation required to improve that decision consistently. This disciplined approach is often the difference between a digital twin that becomes operational infrastructure and one that remains a short-lived pilot project (Fuller et al., 2020; Chen et al., 2023).

Research Roadmap and Future Directions

The next stage of digital twin research in renewable energy and power electronics is likely to be shaped by deeper hybridization between physics-based reasoning and machine learning. The most promising direction is not the replacement of engineering models, but their augmentation through data-driven surrogates, online parameter adaptation, and uncertainty-aware inference. In power electronics, this may enable faster electro-thermal estimation and more robust condition-aware control. In renewable plants, it may

improve the ability to separate environmental variability from underlying technical degradation (Chen et al., 2023; Lei et al., 2023).

A second research direction is composability across scale. Today, many digital twins are still developed as isolated solutions for single assets or narrowly defined services. Future energy systems will require interoperable twins that connect component, asset, plant, microgrid, and system levels without losing semantic coherence. This is particularly relevant in converter-dominated grids, where local device constraints influence feeder behavior, market response, and resilience outcomes. Research on microgrids and future power systems already points toward this layered integration challenge, but much work remains before it can be treated as standard engineering practice (Bazmohammadi et al., 2022; Song et al., 2023; Tao et al., 2019).

The field also needs better validation culture. Open benchmark datasets, reproducible test environments, and shared evaluation metrics are still limited when compared with the ambitions often associated with digital twins. Energy researchers would benefit from benchmark problems that distinguish between monitoring, diagnosis, prognosis, and control uses, because each one imposes different requirements on latency, fidelity, and explainability. Without such discipline, digital twin claims risk becoming too generic to guide design decisions or procurement strategies (Fuller et al., 2020; Do Amaral et al., 2023).

In the longer term, digital twins may become central to sustainable asset management. By making degradation more legible and operations more adaptive, they can help extend useful lifetime, reduce unnecessary replacement, and support refurbishment or second-life decisions for energy equipment. Their strategic importance will therefore depend not only on computational intelligence but also on their ability to embed engineering

accountability into the transition toward cleaner and more software-defined power systems (Onile et al., 2021; Song et al., 2023).

Conclusion

Digital twins have evolved from an attractive conceptual metaphor into a serious engineering framework for renewable energy systems and power electronics. Their real value does not lie in creating a visually impressive digital replica, but in sustaining a trustworthy connection between measurements, models, and decisions across the asset lifecycle. When designed with a clear purpose, they improve observability, support diagnosis and prognosis, and strengthen the operational intelligence of converter-dominated energy infrastructures.

For the energy sector, the most meaningful future of the digital twin is therefore practical rather than symbolic. It is a future in which photovoltaic plants become easier to diagnose, wind turbines become easier to maintain, converters become easier to protect, and microgrids become easier to coordinate. Achieving this future will require rigorous modeling, disciplined data practices, and closer attention to standardization and validation. Yet the direction is clear: digital twins are becoming one of the most important organizing ideas in the design and operation of self-aware energy systems.

Kaynakça/References

- Bazmohammadi, N., Madary, A., Vasquez, J. C., Bazmohammadi, H., Khan, B., Wu, Y., & Guerrero, J. M. (2022). Microgrid digital twins: Concepts, applications, and future trends. *IEEE Access*, *10*, 2284-2302.
<https://doi.org/10.1109/ACCESS.2021.3138990>
- Boschert, S., & Rosen, R. (2016). Digital twin-The simulation aspect. In P. Hehenberger & D. Bradley (Eds.), *Mechatronic futures* (pp. 59-74). Springer. https://doi.org/10.1007/978-3-319-32156-1_5
- Chen, H., Zhang, Z., Karamanakos, P., & Rodriguez, J. (2023). Digital twin techniques for power electronics-based energy conversion systems: A survey of concepts, application scenarios, future challenges, and trends. *IEEE Industrial Electronics Magazine*, *17*(2), 20-36.
<https://doi.org/10.1109/MIE.2022.3216719>
- De Kooning, J., Stockman, K., De Maeyer, J., Jarquin-Laguna, A., & Vandeveldel, L. (2021). Digital twins for wind energy conversion systems: A literature review of potential modelling techniques focused on model fidelity and computational load. *Processes*, *9*(12), Article 2224.
<https://doi.org/10.3390/pr9122224>
- Do Amaral, J. V. S., dos Santos, C. H., Montevechi, J. A. B., & de Queiroz, A. R. (2023). Energy digital twin applications: A review. *Renewable and Sustainable Energy Reviews*, *188*, 113891. <https://doi.org/10.1016/j.rser.2023.113891>
- Fuller, A., Fan, Z., Day, C., & Barlow, C. (2020). Digital twin: Enabling technologies, challenges and open research. *IEEE Access*, *8*, 108952-108971.
<https://doi.org/10.1109/ACCESS.2020.2998358>

- Glaessgen, E. H., & Stargel, D. S. (2012). The digital twin paradigm for future NASA and U.S. Air Force vehicles. *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*. Honolulu, HI, United States. <https://doi.org/10.2514/6.2012-1818>
- Grieves, M., & Vickers, J. (2017). Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. In F.-J. Kahlen, S. Flumerfelt, & A. Alves (Eds.), *Transdisciplinary perspectives on complex systems* (pp. 85-113). Springer. https://doi.org/10.1007/978-3-319-38756-7_4
- Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W. (2018). Digital twin in manufacturing: A categorical literature review and classification. *IFAC-PapersOnLine*, *51*(11), 1016-1022. <https://doi.org/10.1016/j.ifacol.2018.08.474>
- Lei, Z., Zhou, H., Dai, X., Hu, W., & Liu, G.-P. (2023). Digital twin based monitoring and control for DC-DC converters. *Nature Communications*, *14*, 5604. <https://doi.org/10.1038/s41467-023-41248-z>
- Onile, A. E., Machlev, R., Petlenkov, E., Levron, Y., & Belikov, J. (2021). Uses of the digital twins concept for energy services, intelligent recommendation systems, and demand side management: A review. *Energy Reports*, *7*, 997-1015. <https://doi.org/10.1016/j.egy.2021.01.090>
- Peng, Y., Zhao, S., & Wang, H. (2021). A digital twin based estimation method for health indicators of DC-DC converters. *IEEE Transactions on Power Electronics*, *36*(2), 2105-2118. <https://doi.org/10.1109/TPEL.2020.3009600>
- Rasheed, A., San, O., & Kvamsdal, T. (2020). Digital twin: Values, challenges and enablers from a modeling perspective. *IEEE*

Access, 8, 21980-22012.

<https://doi.org/10.1109/ACCESS.2020.2970143>

Song, Z., Hackl, C. M., Anand, A., Thommessen, A., Petzschmann, J., Kamel, O., Braunbehrens, R., Kaifel, A., Roos, C., & Hauptmann, S. (2023). Digital twins for the future power system: An overview and a future perspective. *Sustainability*, 15(6), 5259. <https://doi.org/10.3390/su15065259>

Tao, F., Zhang, H., Liu, A., & Nee, A. Y. C. (2019). Digital twin in industry: State-of-the-art. *IEEE Transactions on Industrial Informatics*, 15(4), 2405-2415

CHAPTER 2

ÇBAG TABANLI RÜZGÂR ÇİFTLİĞİNDE ALT-SENKRON REZONANS DURUMLARININ İNCELENMESİ İÇİN BULANIK MANTIK TABANLI TCSC MODELİNİN GELİŞTİRİLMESİ

BETÜL PEKDEMİR SARIOĞLU¹
M. KENAN DÖŞOĞLU²
MUSTAFA DURSUN³

Giriş

Son yıllarda yenilenebilir enerji kaynaklarının kullanımındaki hızlı artış, fosil yakıtlara olan bağımlılığı azaltarak enerji sektöründe önemli bir dönüşüm başlatmıştır. Bu dönüşüm içinde rüzgâr enerjisi, diğer yenilenebilir kaynaklara kıyasla daha yüksek büyüme oranına sahip olmuş ve enerji politikalarının da desteğiyle küresel ölçekte dikkat çekici bir yayılım göstermektedir (Michael, 2012; Anagnostopoulos et al., 2017). Günümüzde kurulan

¹Öğrenci, Düzce Üniversitesi Mühendislik Fakültesi, Elektrik Elektronik Mühendisliği ABD, Orcid: 0009-0004-4796-2108

²Prof. Dr., Düzce Üniversitesi Mühendislik Fakültesi, Elektrik Elektronik Mühendisliği Bölümü, Orcid: 0000-0001-8804-7070

³Doç. Dr., Düzce Üniversitesi Mühendislik Fakültesi, Elektrik Elektronik Mühendisliği Bölümü, Orcid: 0000-0001-9952-9358

büyük ölçekli rüzgâr santrallerinin önemli bir kısmı Çift Beslemeli Asenkron Generatör (ÇBAG) tabanlıdır. Bu tercihin temelinde düşük evirici kapasitesi, aktif-reaktif gücün ayrı ayrı kontrol edilebilmesi ve değişken rüzgâr hızlarında yüksek verimlilikle çalışabilmesi yatmaktadır (Abdeen, et al., 2022). ÇBAG tabanlı rüzgâr çiftliklerinin enerji iletim hatlarına bağlanmasından dolayı mevcut altyapıların güç aktarım kapasitelerinin artma zorunluluğu ortaya çıkmaktadır. Uzun mesafeli hatlarda bu kapasiteyi ekonomik biçimde artırmak için kullanılan yöntemlerden birisi seri kompanzasyondur (Meng, et al., 2019). Ancak bu uygulama, hat reaktansını düşürerek güç transferini kolaylaştırırken, beraberinde alt-senkron rezonans (SSR) adı verilen kararsızlık durumlarına yol açmaktadır (Chernet, 2018; Phuong, et al., 2025). Bunun ortadan kaldırılması için ÇBAG tabanlı rüzgâr çiftliklerinde farklı yöntemler literatürde uygulanmaktadır. ÇBAG tabanlı rüzgâr sistemlerinde SSR'nin giderilmesi amacıyla şebeke tarafı ve rotor tarafı evirici devrelerine farklı ek sönümlenme modelleri entegre edilmiştir. Farklı seri kompanzasyon oranlarında yapılan analizlerde, ek sönümlenme modellerin her iki evirici devresinde kullanılmasıyla sistem kararlılığının arttığını ve salınımların daha hızlı sönümlendiğini göstermiştir (Mohammadpour & Santi, 2015; Fan & Miao, 2012; Wu, et al., 2012). ÇBAG'da SSR analizinde kullanılan bir diğer yöntem yapay empedans şekillendirme teknikleridir. Düşük rüzgâr hızlarında ve yüksek seri kompanzasyon oranlarında sanal direnç ve sanal endüktans gibi yapay elemanların kullanımı, sisteme eklenen sanal karakteristikler aracılığıyla SSR etkilerinin azaltılması mümkün olmaktadır (Echiheb, et al., 2022). ÇBAG'da farklı rüzgâr hızı ve seri kompanzasyon oranlarında SSR analizlerinde empedans tabanlı Nyquist analizleri ile uzay vektör tabanlı modellemeleri tercih edilmektedir. Sistemin SSR anında, empedans karakteristiğini belirleyen DC-link dinamiklerinin ve kapasitif davranışın kararlılık üzerindeki etkilerini ayrıntılı biçimde ele alınmıştır (Moreno-Sánchez, et al., 2021). ÇBAG'da SSR durumları için farklı kontrol

tabanlı stratejiler uygulanmaktadır. Özellikle deęişken sistem parametrelerinin önceden kestirimi, dayanıklılık ve uyarlanabilir yapıların oluşturulması için aktif dağılım reddedici kontrol ve çeşitli kayan kip kontrol yapıları ilgili çalışmalarda geliştirilmiştir. Geliştirilen bu modeller ile farklı rüzgâr hızı ve farklı seri kompanzasyon oranlarında etkili sonuçlar verdiği görülmüştür (Xu & Zhao, 2019; Faria, et al., 2021; Huang, et al., 2014). ÇBAG tabanlı rüzgâr çiftliğinde özellikle rotor tarafındaki evirici devresinin aktif güce baęlı olarak SSR durumlarında kontrol etmek çok önemlidir. Açısal hız deęişimlerinin aktif güç üzerinde oluşturduğu etkiler farklı rüzgâr hızı ve farklı seri kompanzasyon oranlarındaki etkileşimleri için iki serbestlik derece (2DOF) modelleri geliştirilmiştir. SSR analizlerinde geliştirilen 2DOF modellerin kullanımının önemi ilgili çalışmalarda ortaya konmuştur (Bodapatla, et al., 2024; Moharana, et al., 2014). Yukarıda verilen literatür çalışmalarında genellikle ÇBAG'da SSR durumlarını ortadan kaldırmak için makine modellemesi, rotor ve şebeke tarafındaki evirici devrelerinde çeşitli modeller geliştirilmiştir. Farklı rüzgâr hızı ve farklı seri kompanzasyon oranlarında SSR için harici olarak sisteme entegre edilen cihazlar kullanılmaktadır. Sistemde SSR etkilerini minimum yapmak için Esnek AC İletim sistemi (FACTS) cihazlarından Statik Senkron Kompanzatör (STATCOM), Statik Var Kompanzatör (SVC), Tristör Kontrollü Seri Kompanzatör (TCSC), Gate Kontrollü Seri Kapasitör (GCSC), Birleştirilmiş Güç Akışı Kontrolü (UPFC) ve Statik Senkron Seri Kompanzatör (SSSC) modelleri geliştirilmiştir. Bu cihazların farklı yaklaşımlar ile geliştirilmesi sayesinde hem kararsızlık durumları hem de salınım durumları detaylıca ilgili çalışmalarda ele alınmıştır (Moharana, et al., 2014; Xie, et al., 2014; Rohit, et al., 2023; Abdeen, et al., 2021; Jiang, et al., 2019; Mohammadpour & Santi, 2014).

Bu çalışmada ÇBAG tabanlı rüzgâr çiftliğinde farklı rüzgâr hızı ve farklı seri kompanzasyon oranlarında, sistem

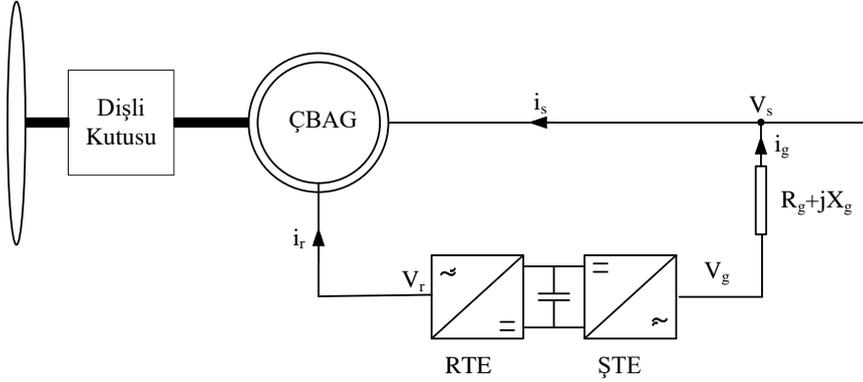
parametrelerindeki belirsizlikler ve çalışma koşullarındaki deęişkenliklere uyum saęlanabilmesi TCSC'nin kontrolü için klasik PI tabanlı bir denetleyici yerine Bulanık Mantık (BM) tabanlı bir denetleyici tasarlanması amaçlanmaktadır. TCSC'nin BM tabanlı olarak kullanılması amaçlanmaktadır. Bu kapsamda, önerilen kontrol yönteminin ve genel sistem davranışının deęerlendirilmesi amacıyla kapsamlı benzetim çalışması MATLAB/Simulink ortamında gerçekleştirilmiştir. Benzetim çalışması modeli, ÇBAG tabanlı bir rüzgâr çiftliği ile seri kompanzasyonlu bir iletim hattını içermekte olup; farklı rüzgâr hızları (9, 12 ve 15 m/s) ve seri kompanzasyon oranları (%60, %70 ve %80) için çeşitli senaryolar oluşturulmuştur.

Bu çalışmanın ilk bölümünde ÇBAG modellemesi ve SSR ele alınırken, ikinci bölümde TCSC'de bulanık mantık denetleyicisi kısmı detaylı olarak açıklanmıştır. Çalışmanın üçüncü bölümünde benzetim çalışması ve elde edilen sonuçları detaylı bir şekilde açıklanmıştır. Son bölümde ise sonuç kısmı irdelenmiştir.

ÇBAG modellemesi ve SSR

ÇBAG tabanlı rüzgâr enerjisi dönüşüm sistemleri, kW seviyesinden MW seviyesine kadar geniş bir güç aralığında enerji üretimi gerçekleştirebilmektedir. ÇBAG yapısı temel olarak dişli kutusu, generatör, Rotor Tarafı Evirici (RTE) ve Şebeke Tarafı Evirici (ŞTE) birimlerinden meydana gelmektedir. ÇBAG'e ait devre yapısı Şekil 1'de sunulmaktadır.

Şekil 1. ÇBAG devre yapısı



Şekil 1’de gösterildiği üzere, ÇBAG’ün stator sargıları doğrudan şebekeye bağlanmaktadır. Rotor devresi ise arka arkaya bağlı evirici yapıları aracılığıyla şebeke ile irtibatlandırılmaktadır. Rotor Tarafı Evirici (RTE) ve Şebeke Tarafı Evirici (ŞTE) birimlerinden oluşan bu evirici yapısı, çift yönlü güç akışına imkân sağlayan ve darbe genişliği modülasyonu (DGM) ile anahtarlanan iki adet gerilim kaynaklı eviriciden oluşmaktadır. ÇBAG sisteminde üretilen aktif gücün kontrolü RTE üzerinden gerçekleştirilirken, DC bara geriliminin düzenlenmesi ŞTE tarafından sağlanmaktadır (Krause, et al., 2002). Hesaplama işlemlerinin sadeleştirilmesi ve benzetim çalışmalarının verimliliğinin artırılması amacıyla, ÇBAG modellemesinde p.u. tabanlı Park–Clark dönüşümleri tercih edilmektedir. Bu çalışmada da Park–Clark dönüşümlerinin hesaplanmasında p.u. büyüklükler kullanılmıştır. ÇBAG’e ait d–q eksenindeki gerilim ve akı denklemleri Denklem (1–8) arasında sunulmaktadır.

$$v_{ds} = R_s i_{ds} + \omega_s \lambda_{qs} + \frac{d}{dt} \lambda_{ds} \quad (1)$$

$$v_{qs} = R_s i_{qs} - w_s \lambda_{ds} + \frac{d}{dt} \lambda_{qs} \quad (2)$$

$$v_{dr} = R_r i_{dr} - s w_s \lambda_{qr} + \frac{d}{dt} \lambda_{dr} \quad (3)$$

$$v_{qr} = R_r i_{qr} + s w_s \lambda_{dr} + \frac{d}{dt} \lambda_{qr} \quad (4)$$

$$\lambda_{ds} = (L_s + L_m) i_{ds} + L_m i_{dr} \quad (5)$$

$$\lambda_{qs} = (L_s + L_m) i_{qs} + L_m i_{qr} \quad (6)$$

$$\lambda_{dr} = (L_r + L_m) i_{dr} + L_m i_{ds} \quad (7)$$

$$\lambda_{qr} = (L_r + L_m) i_{qr} + L_m i_{qs} \quad (8)$$

Burada; v_{ds} , v_{dr} , v_{qs} , v_{qr} sırasıyla d-q stator ve rotor gerilimleri, i_{ds} , i_{dr} , i_{qs} , i_{qr} sırasıyla d-q stator ve rotor akımları, λ_{ds} , λ_{dr} , λ_{qs} , λ_{qr} sırasıyla d-q stator ve rotor kaçak akıları, w_s açılmal hız, s kayma, R_s ve R_r sırasıyla d-q stator ve rotor dirençleri, L_s ve L_r sırasıyla d-q stator ve rotor endüktansları, L_m , manyetik endüktanstır (Bekiroglu & Yazar, 2022).

Uluslararası Elektrik ve Elektronik Mühendisleri Enstitüsü (IEEE) tarafından Alt-Senkron Rezonans (SSR), güç sistemlerinde elektrik şebekesi ile generatör–türbin sistemi arasında, türbin-mil mekanik yapısının senkron frekansın altındaki bir veya birden fazla doğal frekansında meydana gelen enerji alışverişiyle ilişkili bir durum olarak tanımlanmaktadır (Raju, et al., 2017). SSR olgusu, kararlı durum koşullarına bağlı olarak ortaya çıkan SSR ve geçici durumlar sonucunda oluşan SSR olmak üzere iki farklı şekilde sınıflandırılmaktadır. Kararlı durum frekansına bağlı SSR

durumunda, endüvi devresinden geçen alt-senkron frekanslı elektrik akımları rotor devresinde elektromanyetik moment ve akım indüklemekte olup, bu duruma ait frekans (f_r) Denklem (9) ile ifade edilmektedir.

$$f_r = f_s - f_n \quad (9)$$

Burada, f_s senkron frekansı ve f_n rezonans frekansını ifade etmektedir. Doğal frekans ifadesi denklem 10'daki bulunmaktadır.

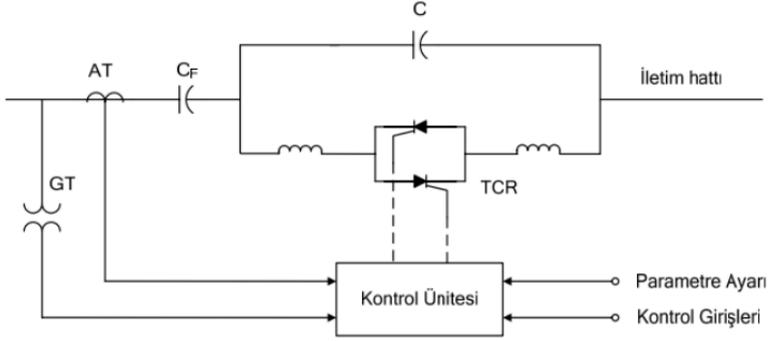
$$f_n = f_s \sqrt{\frac{X_c}{X_1}} \quad (10)$$

Denklem (10)'da, X_c kompanzatör reaktansını, X_1 ise iletim hattına ait seri reaktansı temsil etmektedir. Rotor devresinde indüklenen akımların dolaşımı sonucunda endüvi devresinde alt-senkron gerilim bileşenleri oluşmaktadır. Bu durum, bazı koşullar altında alt-senkron endüvi akımlarının büyümesine neden olarak öz-uyartım veya kararlı durum SSR oluşumuna yol açabilmektedir. Kararlı durum SSR, indüksiyon etkisi ve burulma etkileşimi olmak üzere iki temel alt başlık altında incelenmektedir. Bunun yanı sıra, SSR'nin bir diğer türü geçici durumlarda ortaya çıkmaktadır. Bu durum, rezonans frekans bileşeninin senkron generatörlerin burulma doğal frekanslarından birine yakın olması halinde meydana gelmektedir (Bostani, et al., 2022).

TCSC'de Bulanık Mantık Denetleyicisi

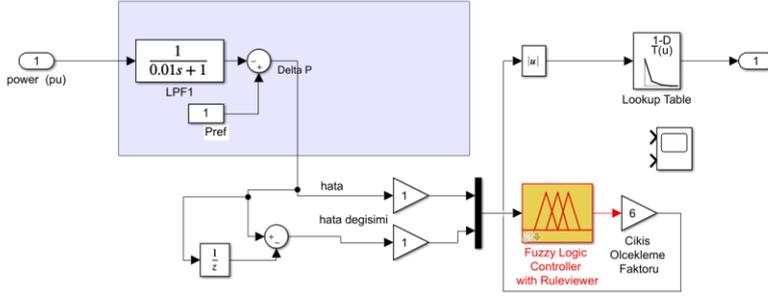
TCSC Esnek AC İletim Sistemi (FACTS) cihazlarından birisidir. Hatta seri olarak bağlanmaktadır. TCSC klasik sabit seri kapasitör yapısını güç elektroniği ile birleştirerek dinamik, hızlı ve hassas bir seri kompanzasyon çözümünü sunmaktadır. TCSC devre modeli Şekil 2'de gösterilmiştir.

Şekil 2. TCSC devre modeli



Şekil 2’de görüldüğü gibi TCSC paralel bağlı bir Tristör Kontrollü Reaktör (TCR) devresi ile seri bağlı bir kapasitörden oluşur. TCR yapısı ise bir endüktans ve anti-paralel bağlı iki tristörden meydana gelir. Tristörlerin tetikleme açısı değiştirilerek reaktörün devreye olan etkisi kontrol edilir. Böylece sistemdeki toplam empedans dinamik olarak ayarlanabilmektedir. Bu yapı sayesinde TCSC özellikle hat empedansını kontrol ederek güç sisteminde hem geçiş süreci hem de kararlı çalışma durumunda performans ve kararlılığa yönelik çok yönlü faydalar sağlamaktadır (Döşoğlu, 2010; Naser, 2017). TCSC'nin temel amaçlarından birisi de iletim hattının efektif reaktansını değiştirerek aktif güç akışını yönlendirmek, güç salınımlarını sönmölemek ve SSR gibi istenmeyen durumları kontrol altına almaktır. Bu yönüyle TCSC sistemin hem kararlılığını artırır hem de enerji iletim hatlarının güvenli şekilde çalışmasını sağlar. Bu çalışmada Bulanık Mantık (BM) denetleyicisinin TCSC devresinde uygulanması amaçlanmıştır. BM tabanlı TCSC denetleyicisinin blok diyagramı Şekil 3’te gösterilmiştir.

Şekil 3. BM tabanlı TCSC denetleyicisinin blok diyagramı



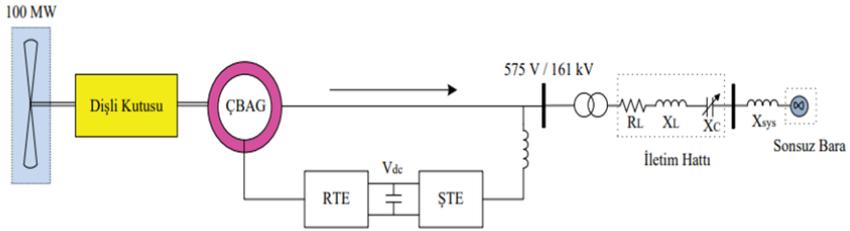
Bu çalışmada geliştirilen bulanık mantık tabanlı denetleyici aktif güç salınımlarının dinamik davranışını izleyerek TCSC'nin kontrol sinyalini uyarlayan bir yapıdadır. Denetleyici iki ana bilgi akışı üzerine kurulmuştur. Bunlar güç salınımlarının filtrelenmiş değeri ve bu değerlerin zaman karakteristiktir. Şekil 3'te gösterilen yapıda ölçülen aktif güç sinyali, yüksek frekans bileşenlerini bastırmak amacıyla birinci mertebeli düşük geçiren filtre (LPF)'den geçirilir. Filtre çıkışı referans güç değeriyle karşılaştırılarak güç hatası (e) oluşturulmaktadır. Bu hata sinyali, SSR modlarını tetikleyen alt-senkron güç salınımlarının büyüklüğü ve yönü hakkında bizlere bilgi vermektedir. Ardışık örnekleme periyotları arasındaki fark alınarak hata değişimi (Δe) üretilir. Bu sinyal sistemdeki güç değişim hızını ve TCSC'nin ne kadar bir düzeltme yapması gerektiğini belirler. Böylece denetleyici yalnızca hatanın büyüklüğüne değil, dinamik eğilimine de duyarlı hâle gelir. Her iki giriş de bulanık çıkarım sistemine uygulanmakta olup, belirlenen üyelik fonksiyonları üzerinden kural tabanıyla eşleştirilmektedir. Bu aşamada güç salınımlarının bastırılması için operatör tarafından tanımlanan uzman bilgisi matematiksel forma dönüştürülmüş olur. Bulanık çıkarım sonucunda elde edilen kontrol işareti çıkış ölçekleme bloğu yardımıyla normalize edilir ve fiziksel sınırlar içine çekilir. Elde edilen son kontrol sinyali ise TCSC'nin ateşleme açısının

belirlenmesinde kullanılarak seri hat empedansının dinamik olarak ayarlanmasını sağlar. Bu yaklaşım sayesinde TCSC alt-senkron modların büyümesini hızla bastırabilmekte ve DFIG tabanlı rüzgâr çiftliğinde SSR etkilerine karşı kararlı bir çalışma bölgesinde tutmaktadır.

Benzetim Çalışması ve Elde Edilen Sonuçları

Bu çalışmada, ÇBAG tabanlı bir rüzgâr çiftliğinde oluşabilecek SSR olayları MATLAB/Simulink ortamında incelenmiştir. ÇBAG tabanlı rüzgâr çiftliğinde gerçekleştirilen benzetim çalışması Şekil 4'te gösterilmiştir.

Şekil 4. ÇBAG tabanlı rüzgâr çiftliğinde gerçekleştirilen benzetim çalışması

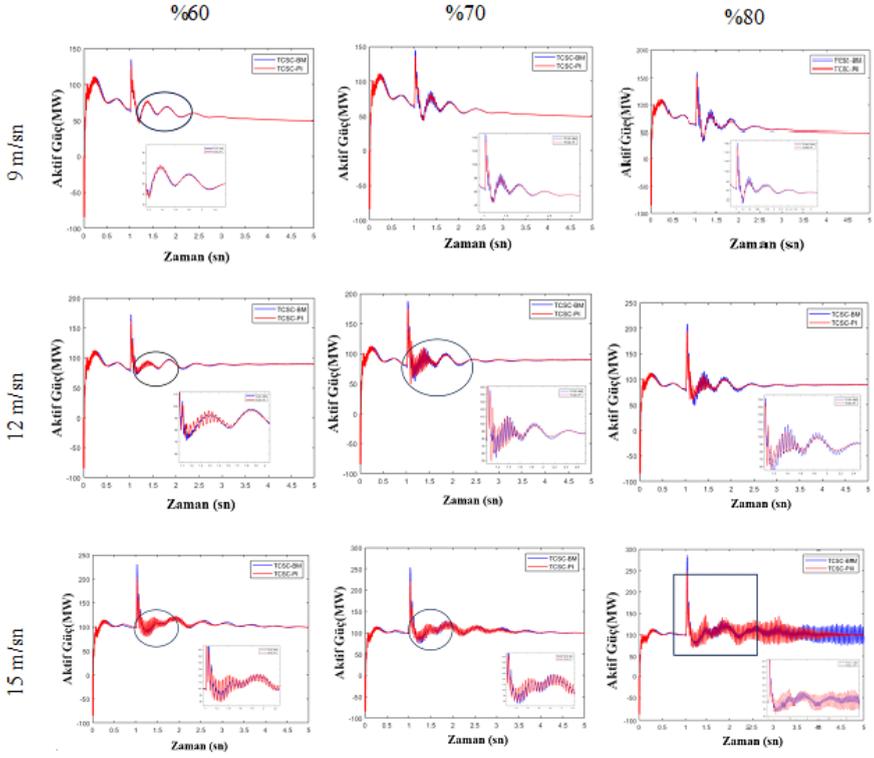


Şekil 4'te her biri 1.5MW gücünde 66 adet türbinden oluşan ve toplamda 100MW kurulu güce sahip bir rüzgâr çiftliği kullanılmıştır. Türbin çıkışlarındaki 575V'luk gerilim 100MVA'lık bir güç transformatörü ile 161kV iletim seviyesine yükseltilmektedir. Çalışma kapsamında SSR oluşumunu incelemek amacıyla iletim hattına kapasitör bağlanmıştır (Abdeen, et al., 2021; Abdeen, et al., 2023). Bu kapasitör farklı senaryolar halinde %60, %70 ve %80 olmak üzere üç farklı seri kompanzasyon oranı olacak şekilde belirlenmiştir. Ayrıca iletim hattına 100MVA gücünde TCSC bağlanmıştır.

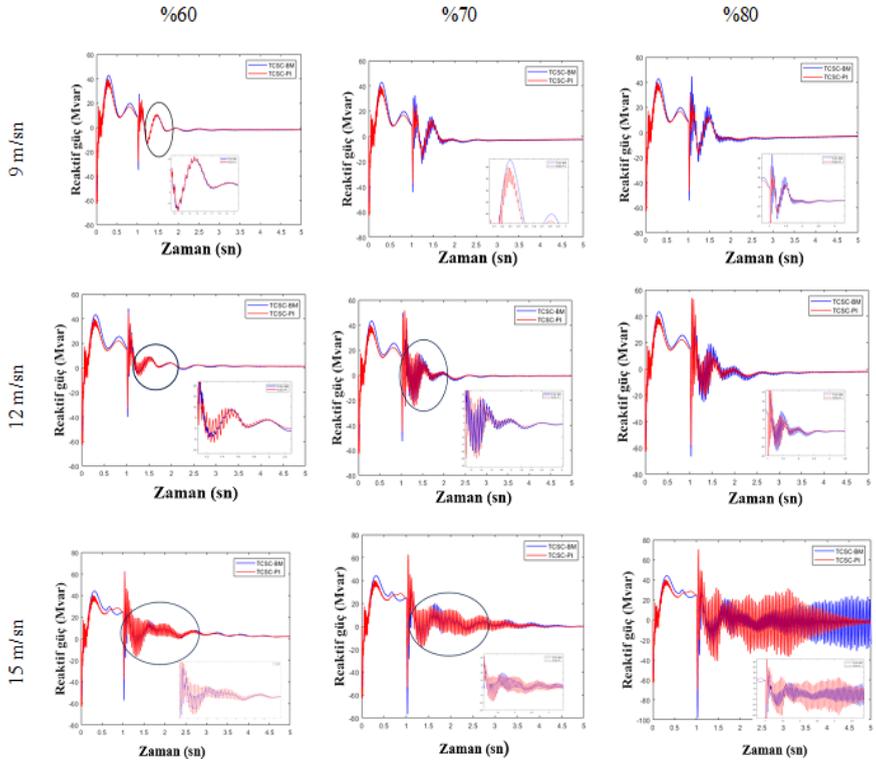
Çalışmada, sistemin hem aerodinamik hem de elektromekanik davranışlarını geniş bir perspektifte görebilmek adına rüzgâr hızları 9 m/s, 12 m/s ve 15 m/s olacak şekilde belirlenmiştir. Yapılan çalışmada 3 faz arızası kullanılmıştır. 3 faz arızası 2 ile 2.1 saniyeler arasında devredir. İletim hattında bulunan kapasitör benzetim çalışmasında 2. saniyede bir kesici sayesinde devreye girmektedir. Yapılan analizde aktif güç, reaktif güç ve DC bara gerilimleri detaylı olarak incelenmiştir.

Benzetim çalışmasında SSR durumları için sistemde TCSC'nin klasik Oransal Integral (PI) ve BM denetleyicilerin kullanılması ile karşılaştırmalar detaylıca incelenmiştir. Karşılaştırmalarda farklı seri kompanzasyon oranları %60, %70 ve %80 ile gösterilirken, farklı rüzgâr hızları 9 m/s, 12 m/s ve 15 m/s olarak gösterilmiştir. Karşılaştırmalardan elde edilen sonuçlar şekil 5 ile şekil 7 arasında gösterilmiştir.

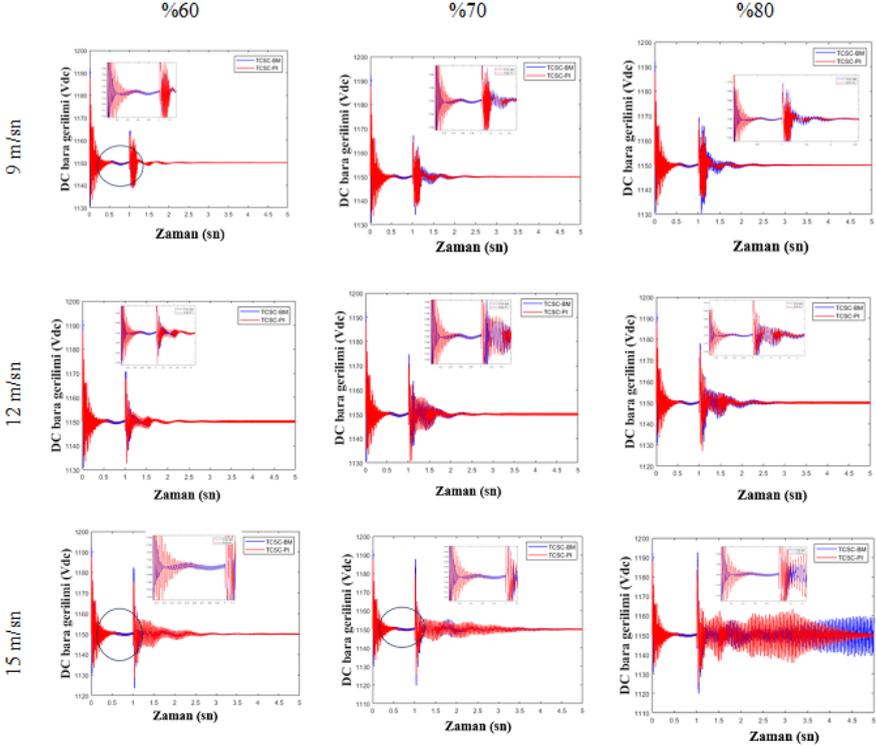
Şekil 5. TCSC'nin PI ve BM denetleyicisi ile aktif güç sonuçları



Şekil 6. TCSC'nin PI ve BM denetleyicisi ile reaktif güç sonuçları



Şekil 7. TCSC'nin PI ve BM denetleyicisi ile DC bara gerilim sonuçları



Şekil 5’de SSR durumunda aktif güç değişimleri, Şekil 6’da SSR durumunda reaktif güç değişimleri, Şekil 7’de SSR durumunda DC bara gerilim değişimleri detaylı olarak incelenmiştir. Benzetim çalışması 5 saniye olarak ayarlanmıştır. ÇBAG’da rüzgâr hızlarının 9 m/s, 12 m/s ve 15 m/s olduğu durumlarda ve seri kompanzasyon oranlarının %60, %70 ve %80 olduğu durumlarda aktif güç, reaktif güç ve DC bara gerilim değişimlerinin hepsinde klasik PI denetleyici ve BM denetleyicinin kullanılmasında sistemin kararlı hale geldiği görülmektedir. Dahası SSR durumundan dolayı meydana gelen salınımların da klasik PI denetleyici ve BM denetleyici sayesinde sönümlendiği görülmektedir. Yakınsama eğrileri detaylıca incelendiğinde klasik PI denetleyicilerde salınımların biraz daha

fazla olduđu gör÷lmektedir. TCSC’de ise yakınsama eğrilerinde gör÷ldüğü salınımların olmadığı gözlemlenmiştir. Şekil 5 ile Şekil 7 arasındaki yapılan karşılaştırmada ÇBAG tabanlı rüzgâr çiftlinde SSR durumunda en çok etki eden seri kompanzasyon oranı ve rüzgâr hızı değerleri detaylı bir şekilde incelenmiştir. Özellikle rüzgâr hızının 15 m/s ve kompanzasyon oranının % 80 olduđu durumlarda sistemde salınımların çok olduđu gör÷lmüştür. Bu değerlerde sistemin daha uzun zamanda kararlı hale geldiği ve salınımların daha uzun zamanda sönümlendiği gözlemlenmiştir. ÇBAG tabanlı rüzgâr çiftlinde SSR durumundaki en az etki eden seri kompanzasyon oranı ve rüzgâr hızı değerleri detaylı bir şekilde değerlendirilmiştir. Özellikle rüzgâr hızının 9 m/s ve kompanzasyon oranının % 60 olduđu durumlarda sistemde salınımların diğer kıyaslamalara göre daha az olduđu gör÷lmüştür. Rüzgâr hızının 9 m/s ve kompanzasyon oranının % 60 olduđu durumlarda sistemin daha kısa zamanda kararlı hale geldiği ve salınımların daha kısa zamanda sönümlendiği gözlemlenmiştir.

Sonuç

ÇBAG tabanlı rüzgâr çiftlinde SSR durumlarında farklı seri kompanzasyon oranları ve farklı rüzgâr hızlarındaki etkileri detaylı olarak incelenmiştir. İletim hattının kapasitif etkisinin oluşturduđu SSR etkisini azaltmak için çeşitli metotlar uygulanmaktadır. Bu çalışmada SSR problemini ortadan kaldırmak için FACTS cihazlarından TCSC kullanılmış olup, farklı denetleyicilerde etkileri detaylı olarak değerlendirilmiştir. Her iki denetleyicide yapılan kıyaslamalarda BM’nin kullanılması ile sistemin daha hızlı bir şekilde kararlı hale geldiği ve SSR durumunda oluşan sonuçların hızlı bir şekilde sönümlendiği gözlemlenmiştir. Klasik PI denetleyici sistem kararlılığı sağlanmasına rağmen, kararlılık ve salınım sönümlenmelerinin daha uzun sürede sağlandığı gör÷lmüştür. Farklı seri kompanzasyon oranları ve farklı rüzgâr hızlarındaki yapılan analizlerde sistemde en çok etkilenen ÇBAG parametresi aktif güç

olurken, en az etkilenen parametre DC bara gerilimi olmuştur. Yapılan bu çalışma SSR çalışmalarında farklı FACTS cihazlarının IEEE benchmark sistemine uygulanabilmesine ve farklı denetleyici yapılarının kullanılarak kararlılık ve salınım sönümlenmelerinin çalışma koşullarına göre belirlenmesine zemin hazırlamaktadır.

Kaynakça

Abdeen, M., El-Banna, S. H. A., Elgohary, S., Mostafa, H., Ghaly, N., Adel, N., ... & Kamel, S. (2022). Adaptive fuzzy supplementary controller for SSR damping in a series-compensated DFIG-based wind farm. *IEEE Access*, 11, 1467-1476.

Abdeen, M., Emran, A., Moustafa, A., Kamal, D., Hassan, R., Hassan, E., ... & Jurado, F. (2021, October). Investigation on TCSC parameters and control structure for SSR damping in DFIG-based wind farm. In *2021 12th International Renewable Energy Congress (IREC)* (pp. 1-5). IEEE.

Abdeen, M., Li, H., Kamel, S., Khaled, A., El-Dabah, M., Kharrich, M., & Sindi, H. F. (2021). A recent analytical approach for analysis of sub-synchronous resonance in doubly-fed induction generator-based wind farm. *IEEE Access*, 9, 68888-68897.

Abdeen, M., El-Dabah, M. A., Domínguez-García, J. L., & Kamel, S. (2023). Gate-controlled series capacitor: A new methodology for mitigating sub-synchronous resonance in a series-compensated DFIG-based wind farm. *IET Renewable Power Generation*, 17(10), 2638-2647.

Anagnostopoulos, P., Spyridaki, N. A., & Flamos, A. (2017). A “New-Deal” for the development of photovoltaic investments in Greece? A parametric techno-economic assessment. *Energies*, 10(8), 1173.

Bekiroglu, E., & Yazar, M. D. (2022). MPPT control of grid connected DFIG at variable wind speed. *Energies*, 15(9), 3146.

Bodapatla, S. K., Sarma, P. M., & Gaddam, M. (2024). A Robust UDE-Based 2DOF Controller for Mitigating Sub-Synchronous Control Interaction in Wind Power Plants. *Electric Power Components and Systems*, 52(4), 610-628.

Bostani, Y., Jalilzadeh, S., Mobayen, S., Rojsiraphisal, T., & Bartoszewicz, A. (2022). Damping of subsynchronous resonance in utility DFIG-based wind farms using wide-area fuzzy control approach. *Energies*, 15(5), 1787.

Chernet, S. (2018). *Subsynchronous Resonance in Doubly Fed Induction Generator Based Wind Farms*. Chalmers Tekniska Hogskola (Sweden).

Döşođlu, M. K. (2010). Rüzgâr santralinde gerilim ve güç kontrolünün facts cihazları ile incelenmesi. Düzce Üniversitesi, Fen Bilimleri Enstitüsü, Yüksek Lisans Tezi, 113s, Düzce.

Echiheb, F., Ihedrane, Y., Bossoufi, B., Bouderbala, M., Motahir, S., Masud, M., ... & ElGhamrasni, M. (2022). Robust sliding-backstepping mode control of a wind system based on the DFIG generator. *Scientific reports*, 12(1), 11782.

Fan, L., & Miao, Z. (2012). Mitigating SSR using DFIG-based wind generation. *IEEE Transactions on Sustainable Energy*, 3(3), 349-358.

Faria, F., Roy, T. K., Khatun, M. M., Sarkar, T., Haque, T., & Hore, A. K. (2021, July). Robust Nonlinear Double Integral Sliding Mode Controller Design for Mitigating SSR in DFIG-Based Wind Farms. In *2021 International Conference on Automation, Control and Mechatronics for Industry 4.0 (ACMI)* (pp. 1-5). IEEE.

Huang, P. H., El Moursi, M. S., Xiao, W., & Kirtley, J. L. (2014). Subsynchronous resonance mitigation for series-compensated DFIG-based wind farm by using two-degree-of-

freedom control strategy. *IEEE Transactions on Power Systems*, 30(3), 1442-1454.

Jiang, H., Song, R., Du, N., Zhou, P., Zheng, B., Han, Y., & Yang, D. (2019). Application of UPFC to mitigate SSR in series-compensated wind farms. *The Journal of Engineering*, 2019(16), 2505-2509.

Krause, P. C., Wasynczuk, O., Sudhoff, S. D., & Pekarek, S. (2002). *Analysis of electric machinery and drive systems* (Vol. 2, pp. 203-210). New York: IEEE press.

Meng, Y., Pan, X., Ma, H., Li, K., Yu, J., & Wang, X. (2019). Analysis and mitigation of subsynchronous resonance based on integral control for dfig-based wind farm. *IET Generation, Transmission & Distribution*, 13(9), 1718-1725.

Michael, S. (2012). *Development of Simplified Models of Doubly-Fed Induction Generators (DFIG). A contribution towards standardized models for voltage and transient stability analysis* (Master's thesis, Chalmers University of Technology).

Mohammadpour, H. A., & Santi, E. (2015). SSR damping controller design and optimal placement in rotor-side and grid-side converters of series-compensated DFIG-based wind farm. *IEEE Transactions on Sustainable Energy*, 6(2), 388-399.

Mohammadpour, H. A., & Santi, E. (2014). Modeling and control of gate-controlled series capacitor interfaced with a DFIG-based wind farm. *IEEE Transactions on Industrial Electronics*, 62(2), 1022-1033.

Moharana, A., Varma, R. K., & Seethapathy, R. (2014). SSR alleviation by STATCOM in induction-generator-based wind farm connected to series compensated line. *IEEE Transactions on Sustainable Energy*, 5(3), 947-957.

Moreno-Sánchez, R., Núñez-Gutiérrez, C. A., Visairo-Cruz, N., Hernández-Ramírez, J., & Segundo-Ramírez, J. (2021). Understanding the origin of SSR in series-compensated DFIG-based wind farms: Analysis techniques and tuning. *IEEE Access*, 9, 117660-117672.

Naser, m. S. A. (2017). Modelling and analysis of facts devices for stability improvement in power system using matlab software.

Phuong, B. T. H., Ngoc, T. T., Thanh, P. H., & Van Dai, L. (2025). Mitigating Subsynchronous Resonance in Doubly Fed Wind Turbine Induction Generator Using FACTS Devices: A Comparative Case Study. *International Journal of Robotics and Control Systems*, 5(1), 311-332.

Rohit, C., Darji, P., & Jariwala, H. R. (2023). A preordainment approach for design of auxiliary damping controller and SSSC tuning to enhance SSR mode stability in DFIG based windfarm. *Smart Science*, 11(3), 605-628.

Raju, D. K., Umre, B. S., Junghare, A. S., & Babu, B. C. (2017). Mitigation of subsynchronous resonance with fractional-order PI based UPFC controller. *Mechanical Systems and Signal Processing*, 85, 698-715.

Wu, Z., Zhu, C., & Hu, M. (2012). Supplementary controller design for SSR damping in a series-compensated DFIG-based wind farm. *Energies*, 5(11), 4481-4496.

Xu, Y., & Zhao, S. (2019). Mitigation of subsynchronous resonance in series-compensated DFIG wind farm using active disturbance rejection control. *IEEE Access*, 7, 68812-68822.

Xie, H., & de Oliveira, M. M. (2014, October). Mitigation of SSR in presence of wind power and series compensation by SVC.

In 2014 International conference on power system technology (pp. 2819-2826). IEEE.

CHAPTER 3

ROBUST DC LINK VOLTAGE CONTROL IN PV INVERTERS: A SLIDING MODE APPROACH

1. ZEYNEP BALA DURANAY¹

2. İSMAİL ANIL AVCI²

3. HANİFİ GÜLDEMİR³

Introduction

The growing global demand for renewable energy has made photovoltaic (PV) systems a crucial technology for sustainable energy generation. Among the various configurations, single-phase standalone or grid-connected PV inverters are commonly used in residential and small-scale applications due to their cost-effectiveness and ease of deployment. A key component in these systems is the DC link voltage, which serves as an energy buffer between the PV array and the inverter. It is essential to maintain a stable and regulated DC link voltage to ensure power quality, efficient energy conversion, and reliable interaction with the grid.

¹ Assoc.Prof.Dr., Firat University, Department of Electrical-Electronics Engineering, Orcid: 0000-0003-2212-5544

² Res.Assist., Firat University, Department of Electrical-Electronics Engineering, Orcid: 0000-0002-2038-4043

³ Prof.Dr., Firat University, Department of Electrical-Electronics Engineering, Orcid: 0000-0003-0491-8348

However, regulating the DC link voltage poses several challenges. The dynamic and intermittent nature of solar irradiance leads to fluctuations in PV output, while grid disturbances and load variations further complicate the control process. These uncertainties require robust and adaptive control strategies that can maintain voltage stability across a wide range of operating conditions.

Traditional linear controllers, such as proportional-integral (PI) controllers, have been widely used for DC link voltage regulation (Sunddararaj et al., 2021). While these controllers are effective under nominal conditions, their performance declines in the presence of parameter uncertainties, nonlinearity, and external disturbances. To overcome these limitations, various advanced control techniques have been proposed in the literature, including model predictive control (MPC) (Hu et al., 2018), fuzzy logic control (Rajendran et al., 2023), and adaptive control schemes (Ahmed et al., 2022). Among these methods, Sliding Mode Control (SMC) stands out as an especially appealing solution due to its inherent robustness, ease of implementation, and finite-time convergence properties (Utkin, 1993).

SMC works by guiding system trajectories to converge on and stay within a specified sliding surface, which is designed based on the desired dynamics of the system. This strategy provides strong robustness against system disturbances and modeling inaccuracies, making it particularly suitable for power electronic applications where fast response and reliability are essential (Alsmadi et al., 2018; Guldemir, 2005). In the context of PV inverters, SMC has been utilized for various control objectives, including maximum power point tracking (MPPT) (Kchaou et al., 2017, inverter current control (Cai et al., 2016), and DC link voltage regulation (Al-Wesabi et al., 2022).

However, SMC does have some limitations. A common challenge is the phenomenon known as "chattering," which is caused

by high-frequency switching and can put stress on power electronic components (Utkin & Lee, 2006; Lee & utkin, 2007). Recent research has focused on addressing this issue using methods such as boundary layer techniques (Boiko, 2013) and higher-order sliding modes (Utkin et al., 2020; Rosales et al., 2021), which enhance the practical applicability of SMC in PV inverter systems.

This study proposes a robust DC link voltage control strategy for single-phase photovoltaic inverters based on sliding mode control. The proposed method aims to achieve high performance in voltage regulation despite varying solar irradiance and load conditions. Simulation results are presented to validate the effectiveness of the controller, demonstrating enhancements in dynamic response, robustness, and reduced chattering.

The effectiveness of the proposed control strategy is assessed through simulations conducted in MATLAB/Simulink under different solar irradiance and load scenarios, showcasing its robustness and dynamic performance.

DC Link Voltage Control

In grid-connected or standalone PV systems, the power conversion process typically involves two main stages: a DC-DC boost converter that regulates the PV array voltage and steps it up to the desired DC level, and a DC-AC inverter that converts the regulated DC power into sinusoidal AC power suitable for AC use or grid injection. The performance and stability of these systems rely heavily on the precise control of the intermediate DC link voltage, which acts as a crucial interface between the two stages.

Maintaining a constant DC link voltage in the presence of variable solar irradiance, load transients, and grid disturbances poses significant control challenges. In conventional systems, PI or Proportional-Resonant (PR) controllers are employed for voltage regulation due to their simplicity and ease of tuning (Essaghir et al.,

2018). However, these linear controllers often fail to deliver robust performance under fast-changing operating conditions and system nonlinearities.

To overcome these limitations, various nonlinear and adaptive control strategies have been explored in the literature. MPC, for example, provides good dynamic response and constraint handling (Hu et al., 2014), but is computationally intensive. Similarly, fuzzy logic and neural network-based controllers offer adaptive behavior but suffer from design complexity and lack of guaranteed stability margins (Rajavel et al., 2021; Sun et al., 2017).

Among the advanced control techniques, SMC has gained significant attention in power electronics due to its robustness against parameter variations, disturbance rejection capability, and finite-time convergence properties (Utkin et al., 2017). SMC has been successfully applied to boost converters, where the system exhibits inherent nonlinearity and time-varying behavior due to changes in irradiance and temperature (Kalimuthukumar et al., 2021). In such applications, SMC ensures that the output voltage of the converter tracks the reference precisely, even under abrupt changes in input conditions.

For example, Kumar et al. (Kumar et al., 2017) demonstrated the superior dynamic performance of SMC in photovoltaic boost converters compared to PI and fuzzy controllers. Similarly, in the inverter stage, SMC has been used to achieve robust current and voltage regulation with fast transient response (Kumar et al., 2015). Research by Yan et al. (Yan et al., 2015) highlights that SMC can significantly improve grid synchronization and reduce total harmonic distortion (THD) in grid-connected inverters.

Specific studies have focused on applying SMC directly to DC link voltage control. Thammasiriroj et al. (Thammasiriroj et al., 2010) proposed a sliding mode-based controller that dynamically

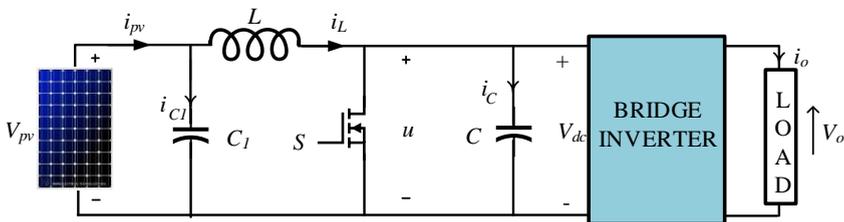
adjusts the duty cycle of the boost converter to maintain a regulated DC link voltage despite fluctuating solar inputs. Their results confirmed the robustness of SMC under sudden shading conditions and load changes.

Additionally, hybrid control strategies have emerged in the literature, combining SMC with other methods such as fuzzy sliding mode (Duranay et al., 2018) disturbance observers (Zhu & Fei, 2018) or adaptive tuning (Gohar &Arbos, 2020) to reduce chattering and improve steady-state accuracy. These studies illustrate that while classical SMC offers a strong foundation for robust control, further refinements are often necessary for practical implementation in PV systems.

Methodology

This study aims to design and evaluate a robust DC link voltage control strategy for a two-stage PV system as seen in Figure 1, comprising a DC-DC boost converter and a single-phase inverter. The proposed control method utilizes SMC to regulate the DC link voltage under variable environmental and load conditions.

Figure 1 PV fed single phase inverter system

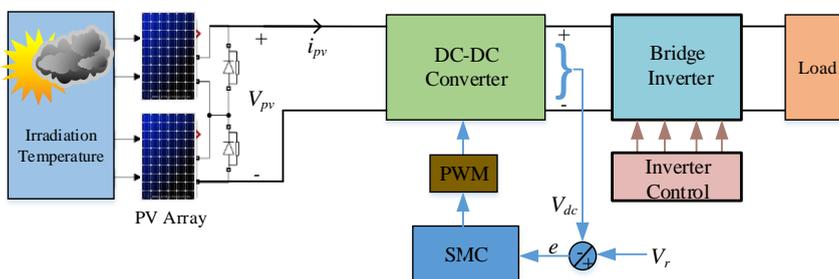


The overall system consists of the following main components:

- **PV Array:** Used the single-diode equivalent circuit, which captures the nonlinear I–V characteristics and variability due to irradiance and temperature.
- **Boost Converter:** Elevates the PV array voltage to a higher DC level suitable for standalone use at grid conditions. Its control directly affects the DC link voltage.
- **DC Link Capacitor:** Acts as an energy buffer between the converter and the inverter.
- **Single-phase Inverter:** Converts the regulated DC voltage into an AC voltage same values as utility grid.
- **Load:** An inductive load is used to evaluate the dynamic performance.

The core of the proposed method lies in the application of sliding mode control to regulate the DC link voltage of single phase inverter. This dc voltage is generated by PV array and boosted to required level by SMC controlled dc-dc boost converter as shown in Figure 2.

Figure 2 DC link regulated PV fed single phase inverter system



In order to maintain the DC link voltage V_{dc} at a reference value V_r , despite variations in solar irradiance or load conditions, the

sliding surface $s(t)$ as shown in Figure 3, is defined based on the voltage error e ,

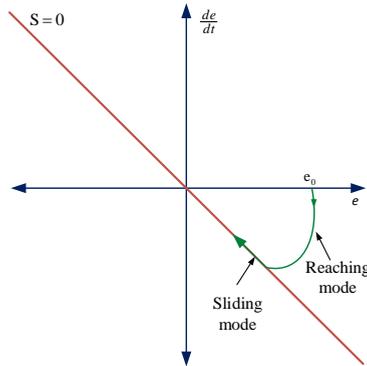
$$e(t) = V_r - V_{dc}(t) \quad (1)$$

and its derivative de/dt :

$$s(t) = \dot{e}(t) + \lambda e(t) \quad (2)$$

where $\lambda > 0$ is a tuning parameter that determines the convergence rate. If $s(t)$ goes zero, the error between V_r and V_{dc} goes zero as well.

Figure 3 Sliding surface



The system reaching the sliding surface and staying on that surface is provided by Lyapunov stability theory. The Lyapunov function is

$$V(t) = \frac{1}{2} s^2(t) \quad (3)$$

The condition to the system to be stable is

$$\dot{V}(t) = s\dot{s} < 0 \quad (4)$$

A discontinuous control input is applied to drive the system, from any initial point e_0 , toward the sliding surface and maintain motion along it:

$$u(t) = u_{eq} - K \cdot \text{sign}(s(t)) \quad (5)$$

where u_{eq} is the equivalent control enables system to be on sliding surface and K is a positive gain that must be carefully selected to ensure stability and robustness without inducing excessive chattering. $K \cdot \text{sign}(s)$ is the force that pulls the system to the sliding surface (Guldemir, 2003).

To reduce the high-frequency switching behavior inherent in traditional SMC, a boundary layer approach is implemented by replacing the sign function with a saturation function (Chen et al., 2002):

$$\text{sign}(s) \rightarrow \text{sat}\left(\frac{s}{\phi}\right) \quad (6)$$

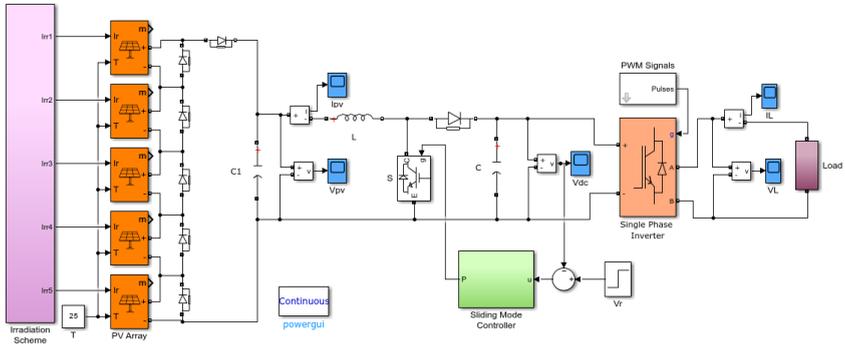
where ϕ defines the width of the boundary layer.

This control law is implemented to govern the duty cycle of the boost converter, ensuring that the DC link voltage remains stable and well-regulated.

Simulation Setup and Results

To validate the proposed control strategy, the system is modeled and simulated in MATLAB/Simulink. The simulation includes accurate representations of the PV array, boost converter, inverter, and associated control loops. The developed Simulink block is shown in Figure 4.

Figure 4 Developed Simulink block



The parameters of the developed system used in simulations are listed in Table 1.

Table 1 Simulation Parameters

Component	Parameter	Value
PV Array	Rated Power	250 W
	V_{mpp}	42.8 V
	I_{mpp}	5.84 A
Boost Converter	Inductance L	3.2 mH
	Capacitance C_{dc}	1 μ F
	Switching Frequency	30 kHz
Inverter	Output Frequency	50 Hz
	DC Link Reference V_{ref}	400 V
Load	Inductive	1mH–400 Ω

The controller is tested under the various scenarios. Firstly, to evaluate the controller's robustness against environmental variability, solar irradiance is varied from 500 W/m² to 1300 W/m² as shown in Figure 5. A step change in solar irradiance, from 800 W/m² to 500 W/m² is applied at t = 0.05 s, from 500 W/m² to 1300

W/m^2 at $t = 0.1$ s and from 1300 W/m^2 to 1000 W/m^2 at $t = 0.15$ s, to evaluate the dynamic response of the control system.

Figure 5 Irradiation pattern

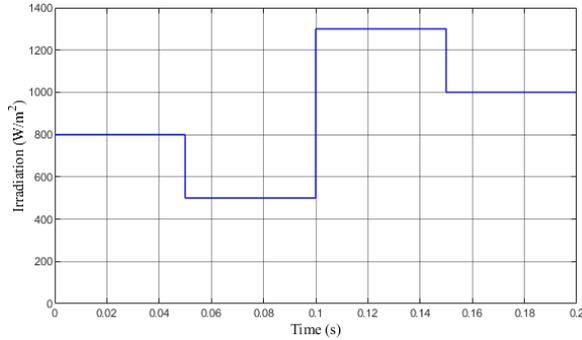
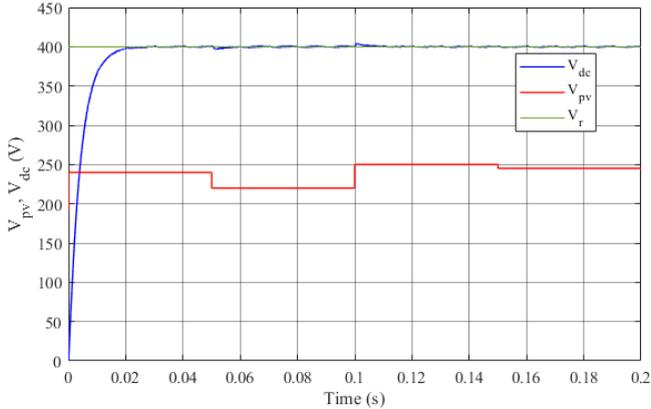


Figure 6(a) shows the PV output voltage corresponding to the irradiation values given in Figure 5 and the DC link voltage of the inverter. Figure 6(b) is the zoom of Figure 6(a) to see the voltage tracking performance.

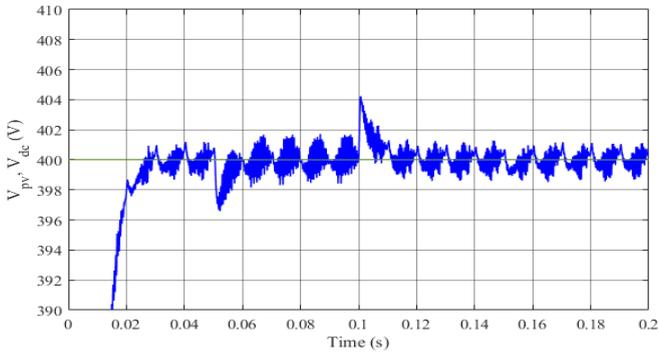
As illustrated in Figure 6 (a), the DC link voltage attains the designated reference value of 400 V and subsequently remains stable throughout the observation period. When the irradiance experiences a sudden decrease or increase, corresponding transient phenomena—namely, a voltage dip during the irradiance drop and a voltage rise during the irradiance increase—are detected at the input of the boost converter. Despite these fluctuations, the SMC strategy employed demonstrates a rapid and effective compensation capability, swiftly restoring the DC link voltage to its nominal reference level as clearly seen in Figure 6 (b). Importantly, this corrective action is achieved without inducing any significant overshoot or oscillations, thereby ensuring the robustness and stability of the voltage regulation under varying irradiance conditions. These results underscore the efficacy of the SMC controller in maintaining voltage stability in the presence of dynamic environmental changes affecting the power input. This

test confirms the robustness of the controller against non-uniform generation conditions, which typically cause power instability.

Figure 6 (a) PV produced voltage and DC link voltage for 400 V reference voltage under various irradianations, (b) Zoom of PV voltage



(a)

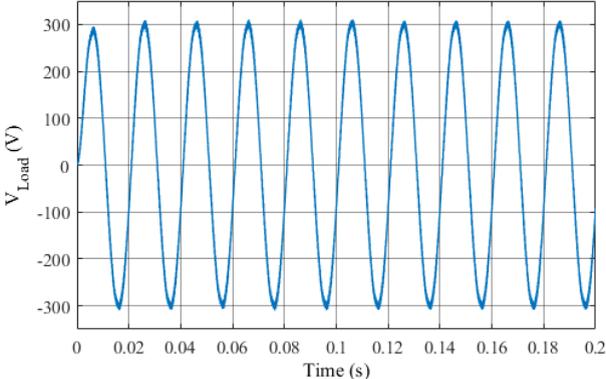


(b)

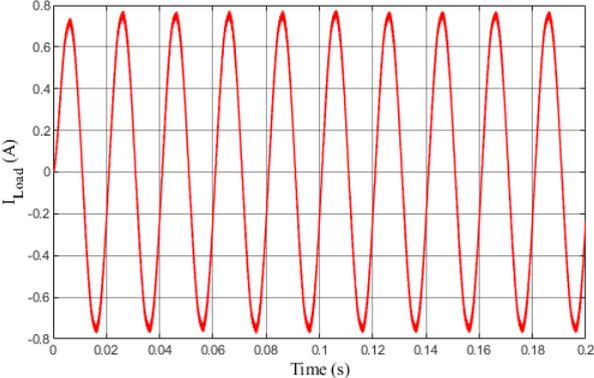
Figures 7(a) and 7(b) present the waveforms of the load voltage and load current, respectively, corresponding to a DC link voltage reference of 400 V. The load voltage waveform exhibits a peak value of approximately 311 V, which aligns with the expected amplitude for the given system parameters. The frequency of both

voltage and current waveforms is maintained at the mains frequency of 50 Hz, indicating proper synchronization with the grid. As observed in Figure 7, both the voltage and current signals display smooth and continuous sinusoidal waveforms, demonstrating the system's ability to generate high-quality power output. Notably, these waveforms remain stable and undistorted despite variations in the input voltage, highlighting the robustness of the control strategy in maintaining consistent load-side performance under fluctuating input conditions. This stability is critical for ensuring reliable operation of connected loads and minimizing power quality issues.

Figure 7 (a) Load voltage and (b) current waveforms



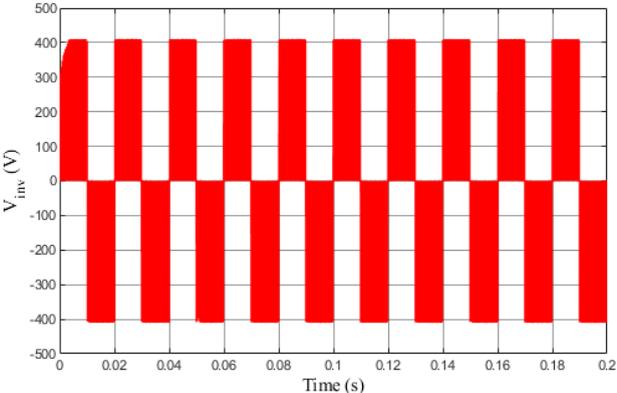
(a)



(b)

As depicted in Figure 8, the voltage measured at the inverter output exhibits a peak-to-peak value of 400 V. This voltage level is indicative of the inverter’s capability to deliver the desired output amplitude in accordance with the system design specifications. Maintaining a stable and precise peak-to-peak voltage at the inverter output is essential for ensuring the proper functioning of downstream electrical components and for achieving efficient power conversion. The consistent voltage amplitude observed further confirms the effectiveness of the inverter control scheme in regulating the output voltage under varying operating conditions, thereby contributing to the overall reliability and performance of the power conversion system.

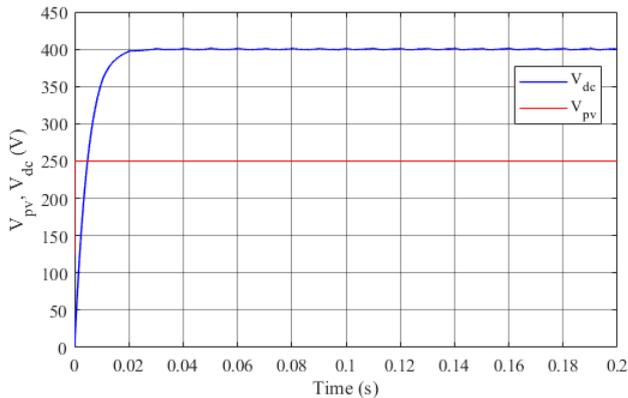
Figure 8 Inverter voltage



To examine the controller’s performance under load disturbances, the inductive load connected to the inverter is altered during the simulation to test voltage stability. At $t=0.1s$ a step load change is applied. At this instant the load connected to the inverter is doubled. During this simulation the irradiation was uniform and kept constant at value of 1000 W/m^2 . The Figure 9 shows the DC link and PV voltages.

Based on the observations from Figure 9, it is evident that change in load have no significant impact on the DC link voltage. This indicates that the system maintains a stable DC link voltage despite variation in load, thereby preserving voltage stability. Consequently, it can be concluded that load fluctuations do not cause noticeable disturbances in the DC link voltage, demonstrating the robustness of the system's performance under varying load conditions.

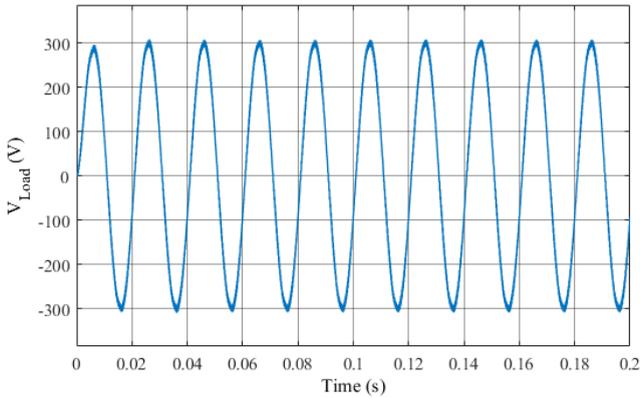
Figure 9 DC link voltage with uniform irradiance under load change at $t=0.1$ s



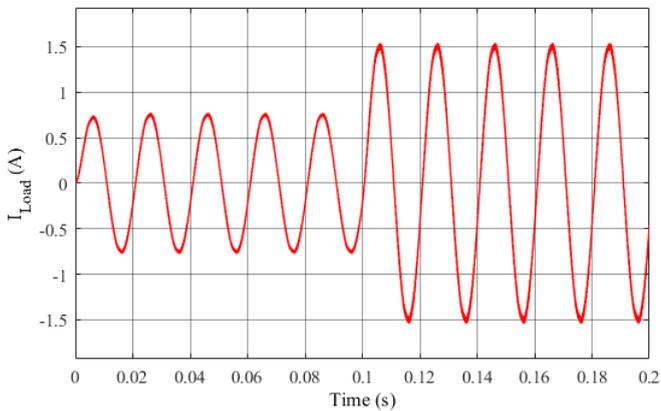
Figures 10(a) and 10(b) illustrate the waveforms of the load voltage and load current, respectively. As observed from these figures, the load voltage remains essentially unaffected by changes in the load, maintaining a stable amplitude throughout the variation. In contrast, the load current exhibits a direct proportionality to the load magnitude; specifically, when the load is doubled at time $t = 0.1$ seconds, the load current correspondingly doubles. This behavior is consistent with the fundamental electrical relationship between current and load, indicating that while the voltage is regulated and held constant, the current adjusts dynamically in response to changes in load demand. These results highlight the system's capability to

sustain voltage stability under varying load conditions while accommodating the necessary current variations.

Figure 10 Waveforms under load change at $t=0.1s$. Is (a) voltage (b) current



(a)

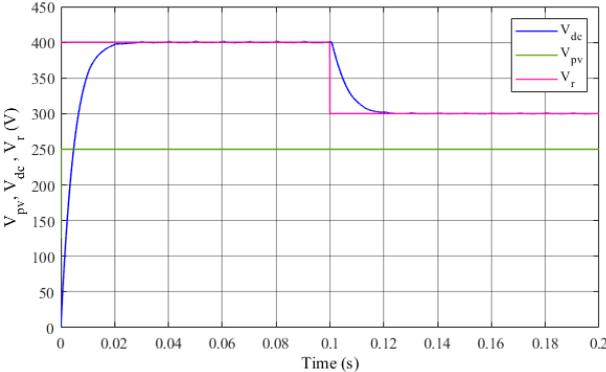


(b)

A step change in the reference voltage from 400 V to 300 V is applied at $t = 0.1$ seconds, and the corresponding response of the DC link voltage is illustrated in Figure 11. As observed from the figure, the controller effectively detects and responds to the sudden

change in the reference input. The DC link voltage rapidly adjusts to the new setpoint, demonstrating a prompt transient response with minimal delay. Furthermore, the controller maintains voltage stability throughout the transition, exhibiting negligible overshoot or undershoot, which indicates robust dynamic performance. This swift and precise regulation highlights the efficacy of the control algorithm in tracking reference variations while ensuring the system's overall stability and reliability under abrupt operating condition changes.

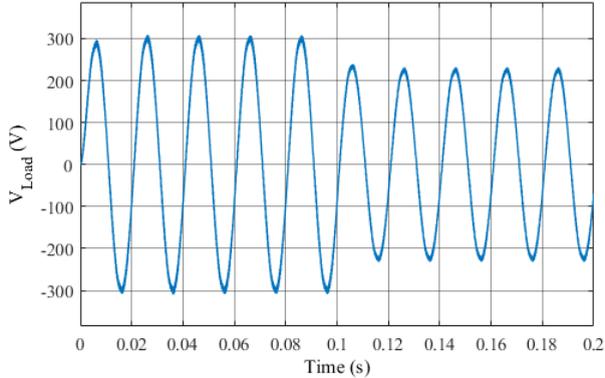
Figure 11 DC link voltage under reference voltage change at $t=0.1s$ from 400V to 300V



As the reference DC link voltage is stepped down from 400 V to 300 V, a corresponding change is observed in the inverter output voltage, which directly influences the amplitude of the sinusoidal load voltage. This relationship is clearly illustrated in Figure 12, where the inverter output voltage transitions smoothly to a new steady-state level in response to the altered DC link reference. Consequently, the load voltage waveform adapts accordingly, maintaining its sinusoidal shape while reflecting the updated voltage magnitude. This behavior demonstrates the effective coordination between the DC link voltage regulation and inverter output control,

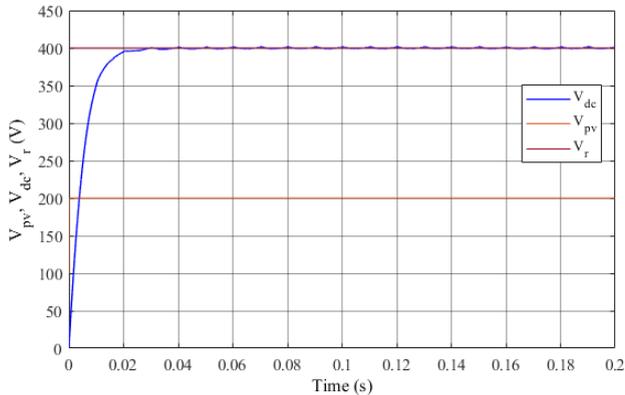
ensuring that the load voltage remains stable and accurately tracks the desired reference values.

Figure 12 Load voltage under reference voltage change at $t=0.1s$ from 400V to 300V



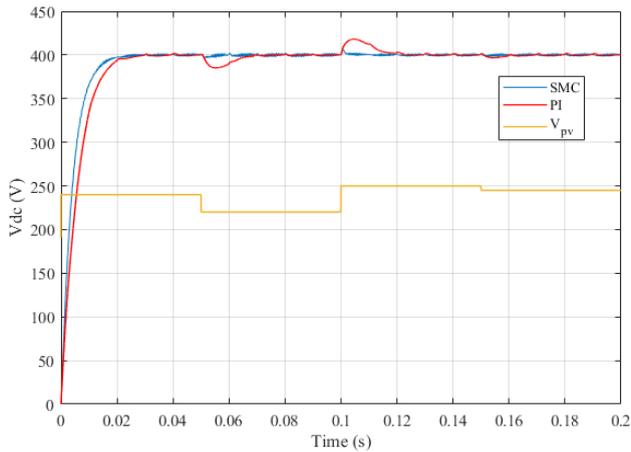
To see the effect of the partial shading the PV panels were subjected to different irradiation values of $PV_1=1200 \text{ W/m}^2$, $PV_2=1000 \text{ W/m}^2$, $PV_3=800 \text{ W/m}^2$, $PV_4=600 \text{ W/m}^2$, $PV_5=400 \text{ W/m}^2$, while the temperature is kept constant at $25 \text{ }^\circ\text{C}$. As the PV voltage output is uniform at a certain level the DC link voltage is smoothly follow the constant reference voltage at 400V as seen in Figure 13.

Figure 13 DC link voltage for partially shaded condition



The performance of the proposed SMC is rigorously evaluated and compared against a conventional PI controller, focusing on key dynamic response metrics such as settling time, overshoot, and steady-state error. As demonstrated in Figure 14, the SMC-based control strategy significantly outperforms the standalone PI controller by achieving a notably faster settling time, which reflects its superior capability to rapidly stabilize the system following disturbances or reference changes.

Figure 14 Performances of the PI and SM controllers



Discussion and Conclusion

The performance of the proposed sliding mode controller for regulating the DC link voltage of a single-phase photovoltaic inverter system equipped with a two-stage power conversion topology, shown in Figure 2, is evaluated through MATLAB/Simulink simulations.

The sliding mode controller was designed to enhance both the dynamic response and steady-state performance under various

operating conditions including irradiance changes, load disturbances, reference DC link voltage change and partial shading scenarios. The conventional PI controller is also benchmarked against SMC strategy.

The simulation results clearly demonstrate the effectiveness of the proposed sliding mode control scheme. The controller is capable of rapidly rejecting disturbances caused by irradiance changes and load dynamics, minimizing steady-state errors.

The SMC exhibits enhanced disturbance rejection characteristics, effectively minimizing transient deviations and maintaining system stability under varying operating conditions. This improved robustness is attributed to the inherent sliding mode control mechanism, which ensures system trajectories are driven toward and maintained on a predefined sliding surface despite parameter variations and external perturbations. Consequently, the sliding mode control approach not only enhances transient performance but also reduces steady-state error, thereby providing a more reliable and resilient control solution compared to traditional PI control methods. The adaptability of the sliding mode controller makes it suitable for the applications where both dynamic and steady-state performance are critical, especially in in grid-connected and standalone PV systems, where both environmental variability and load fluctuations are inevitable.

References

Ahmed, M., Harbi, I., Kennel, R., & Abdelrahem, M. (2022). Dual-mode power operation for grid-connected PV systems with adaptive DC-link controller. *Arabian Journal for Science and Engineering*, 47, 2893–2907. <https://doi.org/10.1007/s13369-021-05916-w>

Alsmadi, Y. M., Utkin, V., Haj-Ahmed, M. A., & Xu, L. (2018). Sliding mode control of power converters: DC/DC converters. *International Journal of Control*, 91(11), 2472–2493. <https://doi.org/10.1080/00207179.2017.1306112>

Al-Wesabi, I., Fang, Z., Wei, Z., & Dong, H. (2022). Direct sliding mode control for dynamic instabilities in DC-link voltage of standalone photovoltaic systems with a small capacitor. *Electronics*, 11(1), 133. <https://doi.org/10.3390/electronics11010133>

Boiko, I. M. (2013). Chattering in sliding mode control systems with boundary layer approximation of discontinuous control. *International Journal of Systems Science*, 44(6), 1126–1133. <https://doi.org/10.1080/00207721.2011.652233>

Cai, F., Lu, D., Lin, Q., & Wang, W. (2016). Control strategy design of grid-connected and stand-alone single-phase inverter for distributed generation. *Journal of Power Electronics*, 16(5), 1813–1820. <https://doi.org/10.6113/JPE.2016.16.5.1813>

Chen, M. S., Hwang, Y. R., & Tomizuka, M. (2002). A state-dependent boundary layer design for sliding mode control. *IEEE Transactions on Automatic Control*, 47(10), 1677–1681. <https://doi.org/10.1109/TAC.2002.803534>

Duranay, Z. B., Guldemir, H., & Tuncer, S. (2018). Fuzzy sliding mode control of DC-DC boost converter. *Engineering, Technology & Applied Science Research*, 8(3), 3003–3007. <https://doi.org/10.48084/etasr.2116>

Essaghir, S., Benchagra, M., & Noureddine, E. B. (2018). Comparison between PI and PR current controllers of a grid-connected photovoltaic system supplying nonlinear load. In *Proceedings of the 3rd International Conference on Smart City Applications* (pp. 1–6). <https://doi.org/10.1145/3286606.3286799>

Gohar Ali, H., & Arbos, R. V. (2020). Chattering-free adaptive sliding mode controller for photovoltaic panels with maximum power point tracking. *Energies*, *13*(21), 5678. <https://doi.org/10.3390/en13215678>

Guldemir, H. (2003). Sliding mode speed control for DC drive systems. *Mathematical and Computational Applications*, *8*(3), 377–384. <https://doi.org/10.3390/mca8030377>

Guldemir, H. (2005). Sliding mode control of DC-DC boost converter. *Journal of Applied Sciences*, *5*(3), 588–592. <https://doi.org/10.3923/jas.2005.588.592>

Hu, J., Xu, Y., Cheng, K. W., & Guerrero, J. M. (2018). A model predictive control strategy of PV-battery microgrid under variable power generations and load conditions. *Applied Energy*, *221*, 195–203. <https://doi.org/10.1016/j.apenergy.2018.03.085>

Hu, J., Zhu, J., & Dorrell, D. G. (2014). Model predictive control of grid-connected inverters for PV systems with flexible power regulation and switching frequency reduction. *IEEE Transactions on Industry Applications*, *51*(1), 587–594. <https://doi.org/10.1109/TIA.2014.2328785>

Kalimuthukumar, S., Rajesh, K., Kannapiran, B., Manikandan, G., Selvameena, R., & Elliot, C. J. (2021). A sliding mode controller-based boost converter for grid-connected solar PV system. In *Proceedings of the 2021 International Conference on Advance Computing and Innovative Technologies in Engineering (ICACITE)* (pp. 1002–1005). IEEE. <https://doi.org/10.1109/ICACITE51222.2021.9404701>

Kchaou, A., Naamane, A., Koubaa, Y., & M'sirdi, N. (2017). Second-order sliding mode-based MPPT control for photovoltaic applications. *Solar Energy*, 155, 758–769. <https://doi.org/10.1016/j.solener.2017.07.007>

Kumar, N., Saha, T. K., & Dey, J. (2015). Sliding-mode control of PWM dual inverter-based grid-connected PV system: Modeling and performance analysis. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 4(2), 435–444. <https://doi.org/10.1109/JESTPE.2015.2497900>

Kumar, N., Saha, T. K., & Dey, J. (2017). Sliding mode control, implementation and performance analysis of standalone PV-fed dual inverter. *Solar Energy*, 155, 1178–1187. <https://doi.org/10.1016/j.solener.2017.07.034>

Lee, H., & Utkin, V. I. (2007). Chattering suppression methods in sliding mode control systems. *Annual Reviews in Control*, 31(2), 179–188. <https://doi.org/10.1016/j.arcontrol.2007.08.001>

Rajavel, A., & Rathina Prabha, N. (2021). Fuzzy logic controller-based boost and buck-boost converter for maximum power point tracking in solar system. *Transactions of the Institute of Measurement and Control*, 43(4), 945–957. <https://doi.org/10.1177/0142331220938211>

Rajendran, S., Thangavel, V., Krishnan, N., & Prabakaran, N. (2023). DC link voltage enhancement in DC microgrid using PV-based high gain converter with cascaded fuzzy logic controller. *Energies*, 16(9), 3928. <https://doi.org/10.3390/en16093928>

Rosales, A., Castillo, I., & Freidovich, L. (2021). Analysis of higher order sliding mode controllers with boundary layer approximation. In *Proceedings of the 2021 60th IEEE Conference on Decision and Control (CDC)* (pp. 7070–7075). <https://doi.org/10.1109/CDC45484.2021.9683424>

Sun, Y., Li, S., Lin, B., Fu, X., Ramezani, M., & Jaithwa, I. (2017). Artificial neural network for control and grid integration of residential solar photovoltaic systems. *IEEE Transactions on Sustainable Energy*, 8(4), 1484–1495. <https://doi.org/10.1109/TSTE.2017.2691669>

Sunddararaj, S. P., Rangarajan, S. S., Subramaniam, U., Collins, E. R., & Senjyu, T. (2021). Performance of P/PI/PID-based controller in DC-DC converter for PV applications and smart grid technology. In *Proceedings of the 2021 7th International Conference on Electrical Energy Systems (ICEES)* (pp. 171–176). <https://doi.org/10.1109/ICEES51510.2021.9383671>

Thammasiroj, W., Nuchkrua, T., & Ruayariyasub, S. (2010). Sliding mode control for stabilizing DC-link of DC-DC converter in photovoltaic systems. In *Proceedings of the 2nd International Symposium on Power Electronics for Distributed Generation Systems (PEDG 2010)* (pp. 347–351). <https://doi.org/10.1109/PEDG.2010.5545764>

Utkin, V. (1993). Sliding mode control design principles and applications to electric drives. *IEEE Transactions on Industrial Electronics*, 40(1), 23–36. <https://doi.org/10.1109/41.184818>

Utkin, V., Guldner, J., & Shi, J. (2017). *Sliding mode control in electro-mechanical systems* (2nd ed.). CRC Press. <https://doi.org/10.1201/9781420065619>

Utkin, V., & Lee, H. (2006). Chattering problem in sliding mode control systems. In *Proceedings of the 2006 International Workshop on Variable Structure Systems (VSS 2006)* (pp. 346–350). <https://doi.org/10.1109/VSS.2006.1644542>

Utkin, V., Poznyak, A., Orlov, Y., & Polyakov, A. (2020). Conventional and high order sliding mode control. *Journal of the Franklin Institute*, 357(15), 10244–10261. <https://doi.org/10.1016/j.franklin.2020.06.018>

Yan, S., Tan, S. C., & Hui, S. Y. R. (2015). Sliding mode control for improving the performance of PV inverter with MPPT—A comparison between SM and PI control. In *Proceedings of the 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe)* (pp. 1–10). <https://doi.org/10.1109/EPE.2015.7309107>

Zhu, Y., & Fei, J. (2018). Disturbance observer-based fuzzy sliding mode control of PV grid-connected inverter. *IEEE Access*, 6, 21202–21211. <https://doi.org/10.1109/ACCESS.2018.2825678>

CHAPTER 4

INFORMATION ABOUT BRUSHLESS DC (BLDC) MOTORS

İSHAK PARLAR¹

Introduction

Brushless direct current (BLDC) motors are increasingly preferred in many areas, including electric vehicles, industrial automation solutions, and household appliances. The main reasons for this growing interest include their higher efficiency, longer service life, robust construction, and lower maintenance requirements compared to classic brushed DC motors. Their high energy efficiency, in particular, allows for more effective power management, reducing energy consumption and lowering operating costs. These advantages make BLDC motors a significant alternative for applications where sustainability goals are paramount and long-term energy savings are expected [1-4].

BLDC motors can be controlled based on speed, position, or torque, depending on the system requirements. Different control strategies and controller structures can be used to drive these motors. Although many advanced control techniques exist in the literature, the proportional-integral-derivative (PID) control method remains

¹Asst. Prof. Dr., Department of Electrical and Electrical Engineering, Van Yuzuncu Yil University, Orcid: 0000-0002-6344-4253

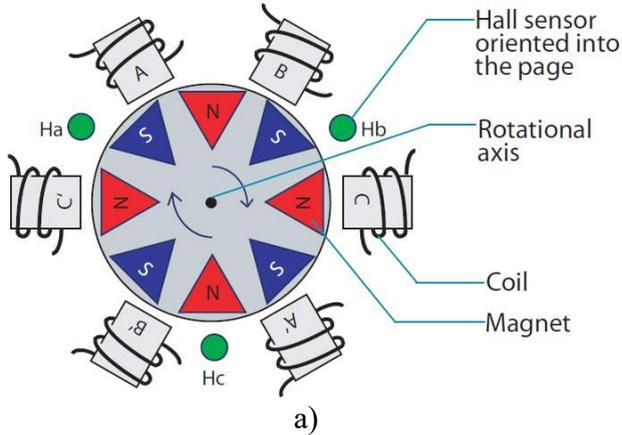
one of the most widely used and preferred control methods in industry due to its simple and stable structure, understandable algorithm, wide range of applications, and easy adaptability to both analog and digital systems.

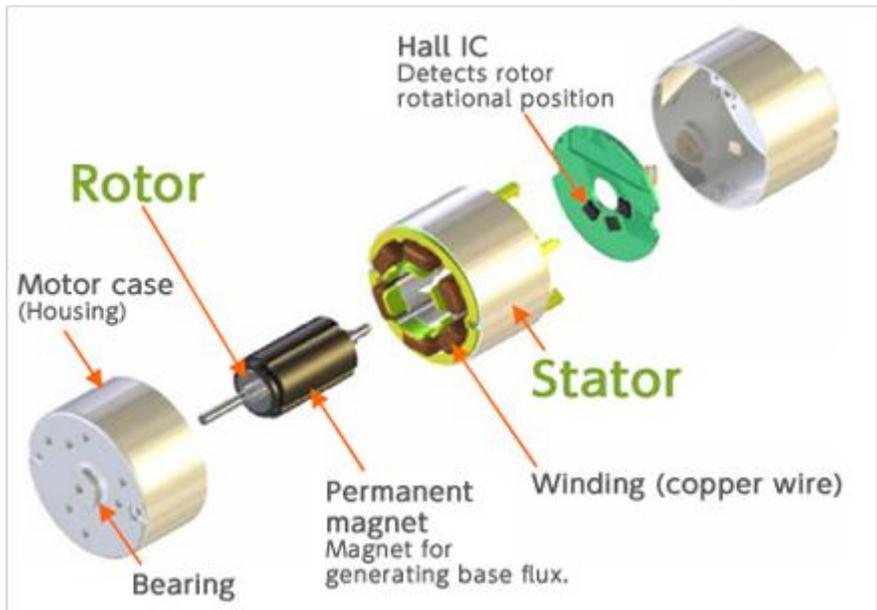
A. BLDC Motors

BLDC motors (Brushless Direct Current Motors), also called brushless direct current motors in Turkish, are a type of electric motor that does not contain mechanical brushes and commutators; switching is performed via electronic circuits [4-10].

In these motors, the rotor is usually constructed with permanent magnets, while the stator consists of three-phase windings. The operating principle relies on switching provided by electronic drives instead of the mechanical brushes used in traditional motors. Thanks to this structure, BLDC motors offer higher efficiency, lower noise levels, and more precise control [11-12].

Kaynak: <https://www.firatdeveci.com/bldc-motorlar-gelecegin-hareket-kaynagi/>





b)

Figure 1 a) Cross-sections of the pole, rotor, and stator structures of a BLDC motors, b) Physical internal structure of a BLDC motors

The figure above show the physical structure and internal pole configurations of the BLDC motors.

A BLDC (Brushless DC) motor essentially consists of two main components:

Rotor (Permanent magnets): This is the part that performs the rotational movement and creates a constant magnetic field.

Stator (Electromagnetic windings): Located in a fixed position; it produces a rotating magnetic field thanks to the electric current passing through it.

The control unit, which manages the motor's operation, acts like the brain of the system. By switching the current in the stator windings at the right time and in the right sequence, it ensures the rotor rotates continuously. This electronic control approach offers precise torque adjustment, fast response time, and high energy efficiency. Therefore, BLDC motors are widely preferred in drones,

electric vehicles, robotic systems, and industrial applications requiring high performance.

To understand why brushless motors have such an important place in modern technologies, it is necessary to examine their working principle. While traditional brushed motors require mechanical contact and friction to transmit current, BLDC motors perform this task entirely electronically. This results in quieter, faster, and more efficient operation [13-19].

BLDC Motor Operating Principle (Step-by-Step)

- **Current Flow Through Stator Windings**

When the motor is energized, electric current flows through the copper coils in the stator, creating a strong electromagnetic field.

- **Rotational Motion via Magnetic Interaction**

The magnetic field created by the stator interacts with the permanent magnets on the rotor. These attractive and repulsive forces cause the rotor to rotate.

- **Continuous Rotation via Electronic Commutation**

The electronic speed controller (ESC) ensures the rotor rotates continuously by sequentially changing the current between the stator windings. This process is performed entirely electronically, without the need for mechanical brushes.

- **Precise Control via Feedback**

Modern BLDC motor systems use sensor- or sensorless feedback methods to determine the rotor position. This allows for highly precise control of speed, torque, and direction.

In brushed motors, current transmission is achieved through brushes and a commutator. This results in disadvantages such as friction, wear, energy loss, and noise. BLDC motors, on the other hand, completely eliminate these mechanical components, managing current through a digital and electronic controller.

This structural difference provides significant advantages such as efficiency, long lifespan, and high performance. These superior qualities make BLDC motors indispensable in modern technologies such as drones, electric vehicles, and automation systems [15-17].

Little-known facts about BLDC motors

Frequency and phase control are required:

- Motor speed → depends on frequency
- Mains AC:
- Constant frequency (50 Hz)
- Constant voltage
- Requires variable speed
- Must have phase sequence and switching control
- Mains AC cannot provide this.

Commutation is essential:

- No brushes
- It must be known when the phases will be energized
- According to rotor position
- With electronic commutation
- If you supply AC directly:
- Rotor position is unknown
- The motor either does not rotate or vibrates

Thanks to the DC+ drive

- Current limit
- Soft start
- Overload protection
- High efficiency is provided

Direct AC supply does not provide this control. A BLDC motor requires a 3-phase AC with controlled frequency and phase to operate.

Why don't we supply AC directly from the mains?

- Constant frequency (50 Hz)
- Uncontrolled phase sequence
- Unknown rotor position
- No torque control
- No protection

A BLDC motor is a DC-powered but synchronous AC motor with magnetic coupling.

Why is BLDC called a "DC motor"?

- Historical and practical naming
- Powered by DC and electronically commuted
- Operating principle is similar to a synchronous AC motor

Frequency indicates how many times an event repeats per second. Phase indicates the position of a periodic wave (AC signal or sine wave) at a point

Does it never work with AC? Actually, it works indirectly:

AC → rectifier → DC → inverter → BLDC

Electromotive Force (EMF) Equation

The voltage induced in the stator windings by the rotor's magnetic field:

$$E = K_e \cdot \omega$$

E : Induced voltage (EMF) (Volts)

K_e : Back EMF constant (Volts / (rad/s))

ω : Rotor angular velocity (rad/s)

Torque Equation

The torque produced by the BLDC motor is proportional to the motor current:

$$T = K_t \cdot I$$

T : Motor torque (Newton·meter, Nm)

K_t : Torque constant (Nm/A)

I : Motor current (Amperes)

Situation Description

The goal is to improve the speed control performance of a BLDC motor. In this process, PID control parameters can be explained by analogy to how a driver controls a vehicle:

Motor: The controlled system (vehicle)

Proportional coefficient (Kp): Accelerator pedal sensitivity; response to instantaneous speed error

Integral coefficient (Ki): Tendency to keep the speed at the reference value; eliminating persistent errors

Derivative coefficient (Kd): Suppressing sudden speed changes; smoothing the system response

Implementation of the Ziegler–Nichols (ZN) Tuning Method

1. Initially, only proportional control is applied.

The integral (Ki) and derivative (Kd) gains are zeroed, and the system is operated only with Kp. At this stage, the speed of the BLDC motor increases and approaches the reference value.

2. The proportional gain is gradually increased.

As the Kp value increases, the system's response speeds up. After a certain point, continuous and regular oscillations in motor speed

are observed. This situation is called critical oscillation and indicates that the system is operating at its stability limit.

3. Critical stability point is determined

At this stage, the motor is not unstable but exhibits undamped periodic oscillations. According to the Ziegler–Nichols method, the proportional gain at this point is defined as the critical gain (K_n or K_u), and the oscillation period is defined as the critical period (T_u).

4. Calculation and application of PID gains

After determining the critical gain value:

K_p is reduced to a certain ratio of the critical value to ensure fast but stable operation of the system.

K_i and K_d gains are added to the system using empirical relationships proposed by Ziegler–Nichols.

Thanks to this method, the BLDC motor achieves stable and smooth speed control, simultaneously providing:

- Fast reference tracking,
- Minimum residual error,
- Reduced oscillation and vibration.

In summary, the Ziegler–Nichols tuning approach is an experimental tuning method that aims to observe dynamic behavior by pushing the system to its limits in a controlled manner and to systematically determine PID parameters based on this critical information [19-21].

A. Cohen–Coon PID Tuning Method: Conceptual Explanation for BLDC Motor Speed Control

System State and Delay Effect

In this scenario, the dynamic behavior of the speed-controlled BLDC motor involves a measurable time delay (dead-time). For example, after the speed reference is applied, the motor begins to physically respond with a delay of approximately 0.2 seconds. Such delays have a decisive effect on the stability of the control system and transient performance.

Basic Principle of the Cohen–Coon Approach

The Cohen–Coon PID tuning method is an experimental and model-based tuning technique developed specifically for delayed systems. In this method, control parameters are determined based on characteristic time magnitudes obtained from the system's step response [22].

The basic steps followed according to the Cohen–Coon method are:

Determination of System Delay and Time Constant

The step response of the motor to the speed reference is examined. Based on this answer:

The time until the response begins is defined as dead time (L),
The time it takes to reach a certain percentage of speed is defined as the time constant (T).

Adjusting Control Gains According to Dynamic Behavior

Using the measured L and T values, proportional (K_p), integral (K_i), and derivative (K_d) gains are calculated through empirical relationships proposed by Cohen–Coon.

In this approach, the sensitivity of the accelerator pedal is matched to the system's delay characteristic.

Ensuring Smooth and Stable Acceleration

Thanks to the obtained PID parameters, the engine exhibits a more balanced and controlled acceleration without creating excessive oscillations despite the delay. The Cohen–Coon method is based on the principle of "If the system is lagging, first quantitatively determine the delay, then adjust the control sensitivity accordingly."

Structural and Functional Advantages of BLDC Motors

BLDC motors were developed to eliminate mechanical commutation elements while maintaining the torque-speed characteristics of conventional direct current (DC) motors. In brushed DC motors, energy transfer to the rotor windings is achieved through a brush-commutator mechanism. This structure leads to:

- Spark generation,
- Periodic maintenance requirements
- Mechanical wear and energy losses

In BLDC motors, however, the function of these mechanical mechanisms is entirely taken over by an electronic controller. Current switching is performed electronically, resulting in higher efficiency, quieter operation, and a longer lifespan.

For the motor to rotate continuously and smoothly, the controller must:

- Trackle the rotor with sufficient switching speed
- Accurately know the instantaneous position information of the rotor

For this purpose, Hall effect sensors are commonly used in BLDC motor systems. These sensors detect rotor position in real time,

providing feedback to the controller and enabling accurate commutation.

Advantages of BLDC (Brushless DC) motors:

- Speed control can be done with constant torque,
- high efficiency
- Due to their brushless structure, there is no friction, no arcing, and no carbon dust production
- smaller in size and have higher torque compared to other motors (requires less copper)
- operate without problems at high speeds
- operate quietly
- generate very little heat
- have a much longer lifespan
- do not require maintenance

Disadvantages of BLDC (Brushless DC) motors:

- a complex control circuit
- require position sensors
- high cost

B. Main Application Areas of BLDC Motors

Brushless direct current (BLDC) motors are widely used today due to their high efficiency, precise speed and torque control, low maintenance requirements, and long service life. They are among the essential drive elements of many modern technological systems, primarily in industrial automation, electric vehicles, and aerospace applications.

Automotive and Transportation, Electric and hybrid vehicles, Electric bicycles, scooters and hoverboards, Steering assistance

systems, Cooling fans and fuel pumps, Industrial Applications, CNC machines, Robotic arms, Conveyor systems, Industrial fans and pumps, Servo motor applications, Robotics and Automation, Electronics and Computer Systems, Computer Cooling Fans, Server Fans, HDD and CD/DVD Drives, Medical Devices, Renewable Energy and HVAC.

D. BLDC Motor Market Trends

A key trend reshaping the global brushless DC motor market is the adoption of advanced motor control units with intelligent connectivity features such as AI-powered algorithms, real-time monitoring, and predictive maintenance. These systems optimize motor performance, improve energy efficiency, and extend product lifespan.

Manufacturers are integrating sensors and intelligent software into BLDC motors to provide dynamic feedback control, wireless diagnostics, and adaptive performance tuning based on load conditions.

For example, in February 2025, Japanese industrial automation firms began using AI-integrated BLDC motors with adaptive control systems in precision robotics. These motors dynamically adjust torque and speed according to varying duty cycles, increasing production efficiency and reducing downtime.

For instance, in August 2024, leading European electric vehicle manufacturers expanded the use of BLDC motors in assisted vehicle systems to reduce energy consumption and extend battery range [16-18].

Kaynak: <https://www.maximizemarketresearch.com/market-report/brushless-dc-motors-market/29301/>

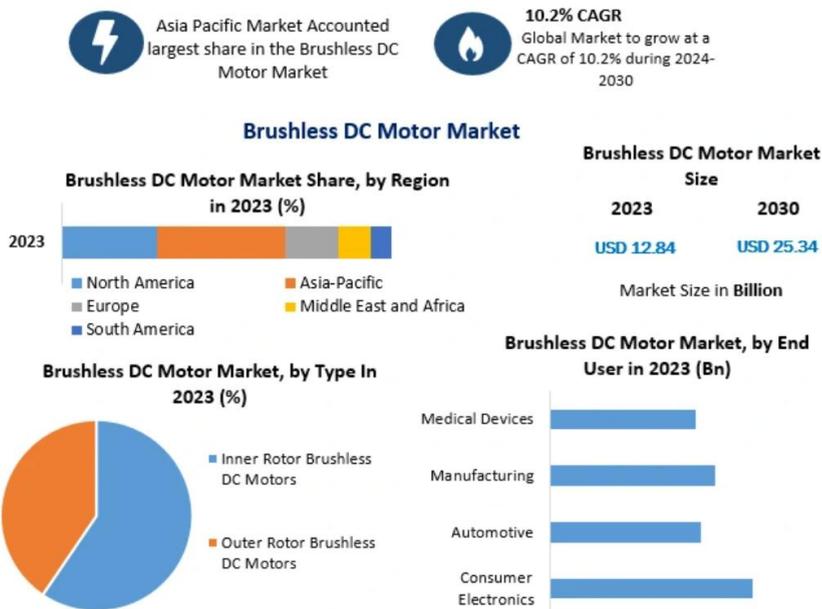


Figure 2 Brushless DC Motor Market: Global Industry Analysis and Forecast (2024-2030)

The Asia Pacific region is projected to dominate the Brushless DC Motor Market in 2024 with a 49.81% revenue share, driven by large-scale industrialization, increased electric vehicle production in China, Japan, and South Korea, and strong growth in the home appliance and HVAC sectors. North America is expected to be the fastest-growing region in the Brushless DC Motor Market throughout the forecast period, driven by stringent energy efficiency regulations, increased investment in industrial automation, and growing demand for high-end electric vehicles and robotics.

Boreasa showcased its groundbreaking slotless (BLDC) motors at the 2025 World Robot Conference. Boreasa achieves precise motor design optimization by leveraging its proprietary

electromagnetic simulation system. This is further enhanced by patented flat-wound litz wire coils, maximum stator utilization, and exceptionally high copper fill rate. The result is motors that deliver impressively high-speed torque and peak efficiencies of up to 92.9%, exceeding industry standards in both power density and efficiency.

Kaynak: <https://www.boreasa.com/>



Figure 3 Slotless BLDC Motors by Boreasa

Nanotec offers integrated brushless DC (BLDC) motors in three different sizes and with nominal power ranges of 52.5 – 940 W. Thanks to their excellent dynamic performance, these intelligent brushless DC servo motors are ideal for applications requiring rapid acceleration, such as medical engineering, automation, robotics, or custom machine building.

Kaynak: <https://calti.ca/smart-servo-stepper-blcd/>



Figure 4 Smart Al Blcd Motor by Nanotec

CONCLUSION

Research shows that parameters such as magnet type and stator slot number in BLDC motor design are optimized to reduce torque ripple and increase energy efficiency. New research methods (e.g., transformer-based learning) aim to predict the speed and position of BLDC motors without using sensors, which helps to reduce costs and design more compact systems.

In conclusion, brushless DC (BLDC) motors, with their high efficiency, precise controllability, low maintenance requirements, and adaptability to advanced electronic control systems, have become a key enabling technology for modern industrial, automotive, and aerospace applications.

References

- [1] Alekseeva, N., Tanev, I., Shimohora, K. (2019). Algorithms for PID controller 2019. In A. Dounis (Ed.), Pd steering controller utilizing the predicted position on track for autonomous vehicles driven on slippery roads (pp.60-77). MDPI: Basel, Switzerland.
- [2] Singh, I. (2024). *BLDC (Brushless Direct Current) Motors*. Pencil.
- [3] Bolton, W., (2021). Instrumentation and control systems (3rd ed.). Elsevier: Oxford, UK.
- [4] Kumbasar, T. (2016). Interval value type-2 fuzzy PID controllers and an online self-tuning mechanism. Pamukkale University Journal of Engineering Sciences[online], 22(8), pp. 643-649. Available from: <https://doi.org/10.5505/pajes.2016.49344>
- [5] Shah, P., Agashe, S. (2016). Review of fractional PID controller. *Mechatronics*, 49, 29-41. Şengül, Ö. (2023). Position control of a suspended pendulum system with PID and fuzzy logic controllers, Master's thesis. Van Yüzüncü Yıl University, Institute of Science, Van, Turkey.
- [6] Yalçın, N., Çakır, S., Kesler, M., Kazak, N. (2012). Determination of PID parameters with gravitational search algorithm. Eleco 2012 Electrical-Electronics and Computer Engineering Symposium, Bursa, Turkey.
- [7] Şen, M., & Mutluer, M. (2025). *A review of BLDC motors: Types, application, failure modes and detection*. *Energies*, 18(24), 6402. <https://doi.org/10.3390/en18246402>

- [8] Buyukyildiz, C., & Saritas, I. (2020). *Sensorless brushless DC motor control using type-2 fuzzy logic. International Journal of Intelligent Systems and Applications in Engineering*, 8(4), 184–190. <https://doi.org/10.18201/ijisae.2020466311>
- [9] Agarwal, P. (2013). *Brushless DC motor speed control using proportional-integral and fuzzy controller. IOSR Journal of Electrical and Electronics Engineering*, 5(5), 68–78. <https://doi.org/10.9790/1676-556878>
- [10] de la Cruz Soto, J., Gascon-Avalos, J. J., Rumbo-Morales, J. Y., Ortiz-Torres, G., Zurita-Gil, M. A., Sorcia-Vázquez, F. D. J., Pérez-Ramírez, J., Valle-López, O. A., Garcia-Castro, S. E., & Buenabad-Arias, H. M. (2025). *Analysis and assessment of a brushless DC outrunner motor for agriculture drones using JMAG. Applied System Innovation*, 8(3), 81. <https://doi.org/10.3390/asi8030081>
- [11] Czmil, S. (2022). *Control and constructions of brushless direct-current motors. Advances in IT and Electrical Engineering*, 27(38-1-2). <https://doi.org/10.7862/re.2020.2>
- [12] Aydoğdu, Ö., Bayer, M., Mühendisliği, E. E., & Üniversitesi, B. S. (2008). PIC Tabanlı Fırçasız DC Motor Sürücüsü Tasarımı. *Elektrik-Elektronik Mühendisliği Bölümü, Selçuk Üniversitesi, Konya*.
- [13] Alaca, Ö., Selbaş, R., & Türkkalesi, M. (2022). FIRÇASIZ MOTOR SÜRÜCÜLERİN ENERJİ VERİMLİLİĞİ. *Uluslararası Sürdürülebilir Mühendislik ve Teknoloji Dergisi*, 6(1), 1-9.
- [14] Ulu, B. (2011). *Fırçasız doğru akım motor (BLDC) hız kontrolü* (Master's thesis, Inonu University (Turkey)).
- [15] Motorlar, S. S. Fırçasız Sürekli Mıknatıslı DC ve AC Senkron Motorlar.

- [16] Erişim Tarihi: 14.01.2026. <https://pdfs.semanticscholar.org/0c8b/b346627564fc527e5dc397472bba976c440c.pdf>
- [17] Erişim Tarihi: 14.01.2026. <https://www.kollmorgen.com/tr-tr/blogs/dc-bl-dc-ve-ac-servo-motorlar-arasindaki-farklar-nelerdir>
- [18] Erişim Tarihi: 15.01.2026. <https://www.cnc-marketi.com/blog/fircasiz-dc-motorlar-avantajlari-ve-uygulamaları#:~:text=F%C4%B1r%C3%A7as%C4%B1z%20DC%20motorlar%2C%20geleneksel%20f%C4%B1r%C3%A7al%C4%B1,bir%20kontrol%20%C3%BCnitesi%20yer%20al%C4%B1r.>
- [19] Mohanraj, D., Arul David, R., Verma, R., Sathiyasekar, K., Barnawi, A. B., Chokkalingam, B., & Mihet-Popa, L. (2022). A review of BLDC motor: state of art, advanced control techniques, and applications. *Ieee Access*, *10*, 54833-54869.
- [20] Al Mashhadany, Y. I. M., Abbas, A. K., & Algburi, S. S. (2022). Modeling and analysis of brushless DC motor system based on intelligent controllers. *Bulletin of Electrical Engineering and Informatics*, *11*(6), 2995-3003.
- [21] Akrami, M., Jamshidpour, E., Nahid-Mobarakeh, B., Pierfederici, S., & Frick, V. (2024). Sensorless control methods for BLDC motor drives: A review. *IEEE Transactions on Transportation Electrification*, *11*(1), 135-152.
- [22] Bhardwaj, L., Mishra, A., & Asija, D. (2025). Parameter Optimisation of PID Controller Utilised for Speed Control of DC Motor with Ziegler-Nichols and Cohen-Coon Tuning Method. In *Intelligent and Sustainable Power and Energy Systems* (pp. 72-80). CRC Press.

