

DC-Link Dynamics Examination of the Parallel-Connected Three-Phase Inverters in Islanded and Grid-Connected Modes

Seyfullah DEDEOĞLU^{1*} 

¹Hitit University, Faculty of Engineering, Department of Electrical and Electronics, Çorum, Turkey

Article Info

Research article
Received: 10/02/2024
Revision: 09/03/2024
Accepted: 18/03/2024

Keywords

Microgrids
Parallel-connected Three-
phase Inverters
DC-link Dynamics
Islanded and Grid-
connected Modes
Voltage Sag

Makale Bilgisi

Araştırma makalesi
Başvuru: 10/02/2024
Düzeltilme: 09/03/2024
Kabul: 18/03/2024

Anahtar Kelimeler

Mikro Şebekeler
Paralel Bağlı Üç Fazlı
Eviriciler
DC-link Dinamikleri
İzole ve Şebekeye Bağlı
Modlar
Voltaj Düşümü

Graphical/Tabular Abstract (Grafik Özet)

This study introduces an improved method for AC microgrids with parallel three-phase inverters, focusing on DC-link voltage control and current limitation. Unlike existing methods, it can limit dq axis currents under all conditions, enhancing system stability and security, as demonstrated in simulation studies. / Bu çalışma, paralel üç fazlı eviricilere sahip AC mikro şebekeler için DC-link gerilim kontrolü ve akım sınırlama üzerine odaklanan geliştirilmiş bir yöntemi tanıtmaktadır. Önerilen yöntem, mevcut yöntemlerin aksine, tüm koşullar altında dq eksen akımlarını sınırlamakta, sistem kararlılığını ve güvenliğini garanti altına almaktadır. Bu durumlar simülasyon çalışmaları ile incelenmiştir.

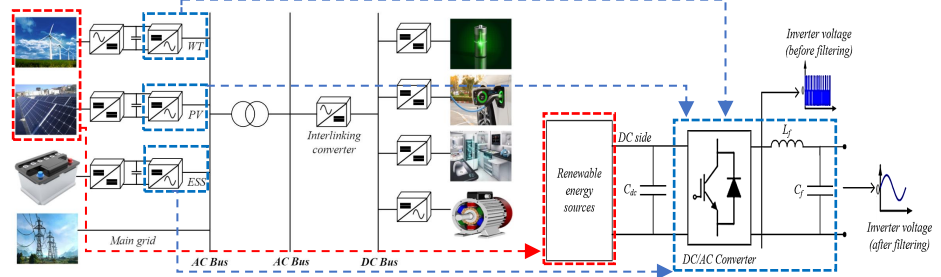


Figure A: Role of inverters in a modern microgrid / Şekil A: Modern mikro şebekelerde eviricilerin rolü

Highlights (Önemli noktalar)

- This study targets DC-link voltage and dq-axis current control in microgrids to ensure grid stability during disturbances and mode transitions. / Bu çalışma, mikro şebekelerde DC-link voltajı ve dq-ekseni akım kontrolünü hedefler, bozucu olaylar ve mod geçişleri sırasında şebeke kararlılığını sağlar.
- An enhanced control strategy combining a lead compensator mechanism with saturation-based current limitation is proposed. / Lead kompensatör mekanizması ile satürasyon tabanlı akım sınırlamayı birleştiren geliştirilmiş bir kontrol stratejisi önerir.
- It is shown through simulations that the strategy's effectiveness in reducing voltage fluctuations and current peaks, minimizing the need for protection relays. / Simülasyonlar aracılığıyla, voltaj dalgalanmaları ve akım piklerini azaltma, koruma rölelerine olan ihtiyacı minimize etme etkinliği gösterilmiştir.

Aim (Amaç): The aim of this study is to develop an improved control strategy for DC link voltage regulation and dq-axis current limitation in microgrids, enhancing stability and efficiency across various operational modes and grid disturbances. / Bu çalışmanın amacı, mikro şebekelerde DC-link voltaj kontrolü ve dq-ekseni akım sınırlaması için bir kontrol stratejisi geliştirmek, çeşitli sistem modları ve şebeke bozucuları boyunca kararlılığı ve verimliliği artırmaktır.

Originality (Özgünlük): This article presents an innovative control strategy, merging a lead compensator-like mechanism with saturation-based current limitation, for microgrid stability enhancement. / Bu makale, mikro şebeke stabilitesini artırmak için lead kompensatör benzeri bir mekanizmayı satürasyon tabanlı akım sınırlama ile birleştiren yenilikçi bir kontrol stratejisi sunmaktadır.

Results (Bulgular): It is demonstrated that the proposed DC-link controller significantly outperforms the existing method in regulating DC-link voltage and limiting dq axis currents, enhancing microgrid reliability and stability across various operational scenarios. / Bu çalışmada önerilen DC-link kontrolör, çeşitli sistem senaryoları boyunca mikro şebeke güvenilirliğini ve kararlılığını artırarak DC-link voltajını düzenleme ve dq eksen akımlarını sınırlama konusunda mevcut yöntemden önemli ölçüde daha iyi bir performans göstermiştir.

Conclusion(Sonuç):

This study presented a novel AC microgrid controller that enhances system stability and reliability, outperforming existing methods. / Bu çalışma, sistem kararlılığını ve güvenilirliğini artıran, mevcut yöntemlerden üstün yeni bir AC mikro şebeke kontrolörü sunmuştur.



DC-Link Dynamics Examination of the Parallel-Connected Three-Phase Inverters in Islanded and Grid-Connected Modes

Seyfullah DEDEOĞLU^{1*}

¹Hitit University, Faculty of Engineering, Department of Electrical and Electronics, Çorum, Turkey

Article Info

Research article
Received: 10/02/2024
Revision: 09/03/2024
Accepted: 18/03/2024

Keywords

Microgrids
Parallel-connected Three-phase Inverters
DC-link Dynamics
Islanded and Grid-connected Modes
Voltage Sag

Abstract

This paper presents a comprehensive analysis of an AC microgrid setup, consisting of parallel three-phase inverters. It introduces a novel controller that integrates the tasks of controlling the DC-link voltage and implementing a current limiting approach. The proposed design, which draws inspiration from the attributes of lead compensators, has a dual objective of controlling the DC-link voltage to mitigate undesired power transfer among the parallel inverters and ensuring the current-limiting ability of all inverters, regardless of the microgrid's operating state. This includes both standalone and grid-connected modes, voltage sags in the grid side, as well as transitional intervals between the two. In contrast to existing DC-link voltage control methods that do not incorporate a current limiting strategy, the proposed solution effectively restrains the dq axis current values in all operating conditions. This is crucial for preserving system stability, avoiding abrupt changes in DC-link voltage and current during sudden grid modifications and transitions. The implementation of Matlab/Simulink studies highlights the critical role of the controller algorithm in mitigating fluctuations in DC voltage and AC current during grid perturbations, as well as preventing the undesired activation of protection relays. Through extensive analysis, the controller demonstrates superior performance compared to existing methodologies, thus highlighting its potential in improving the resilience and efficiency of microgrids. Moreover, the adaptability of the proposed controller to various operational scenarios is demonstrated, emphasizing its versatility and practicality in real-world applications. Overall, the results confirm the effectiveness of the controller in stabilizing the system, minimizing fluctuations in DC-link voltage, and limiting the AC-side dq axis currents for each inverter without the risk of protection relay tripping in all operation modes.

İzole ve Şebekeye Bağlı Modlarda Paralel Bağlı Üç Fazlı Eviricilerin DC-Link Dinamiklerinin İncelenmesi

Makale Bilgisi

Araştırma makalesi
Başvuru: 10/02/2024
Düzeltilme: 09/03/2024
Kabul: 18/03/2024

Anahtar Kelimeler

Mikro Şebekeler
Paralel Bağlı Üç Fazlı Eviriciler
DC-link Dinamikleri
İzole ve Şebekeye Bağlı Modlar
Voltaj Düşümü

Öz

Bu makale, paralel üç fazlı invertörlerden oluşan bir AC mikro şebeke kurulumunun kapsamlı bir analizini sunmaktadır. DC-link voltajının kontrol edilmesi ve bir akım sınırlama yaklaşımının uygulanması görevlerini entegre eden yenilikçi bir kontrolör tanımlanmaktadır. Önerilen tasarım, lead kompanzatorların özelliklerini kullanarak, paralel eviriciler arasındaki istenmeyen güç transferini azaltmak için DC-link voltajını kontrol etme ve mikro şebekenin çalışma modundan bağımsız olarak tüm eviricilerin akım sınırlama yeteneğini sağlama hedeflerine sahiptir. Önerilen yöntem izole ve şebekeye bağlı modları, şebeke tarafındaki voltaj düşüşlerini ve iki çalışma modu arasındaki geçiş durumlarını incelemiştir. Bir akım sınırlama stratejisi içermeyen mevcut DC-link voltaj kontrol yöntemlerinin aksine, önerilen çözüm, tüm işletim koşullarında dq eksen akım değerlerini etkili bir şekilde kısıtlar. Bu, sistem stabilitesini korumak, ani şebeke değişiklikleri ve mod geçişleri sırasında DC-link voltajı ve AC akımlardaki ani değişikliklerden kaçınmak için hayati öneme sahiptir. Matlab/Simulink çalışmalarının uygulanması, şebeke bozulmaları sırasında DC voltajı ve AC akımındaki dalgalanmaları hafifletmede, aynı zamanda koruma rölelerinin istenmeyen aktivasyonunu önlemede kontrolör algoritmasının kritik rolünü kanıtlamıştır. Kapsamlı analizler aracılığıyla, kontrolör mevcut yöntemlere kıyasla üstün performans sergileyerek, mikro şebekelerin dayanıklılığını ve verimliliğini artırma potansiyelini vurgular. Ayrıca, önerilen kontrolörün çeşitli sistem senaryolarına uyum sağlama yeteneği gösterilerek, çok yönlülüğü ve gerçek dünya uygulamalarındaki pratikliği vurgulanmıştır. Genel olarak, sonuçlar kontrolörün sistemi stabilize etme, DC-link voltajındaki dalgalanmaları en aza indirme ve tüm sistem modlarında koruma rölesi tetikleme riski olmadan her evirici için AC taraf dq eksen akımlarını sınırlama etkinliğini doğrulamaktadır.

1. INTRODUCTION (GİRİŞ)

Three-phase inverters play a critical role in both microgrids and smart grids, serving as key components in the integration of renewable energy sources and the effective management of power flow [1-2]. In microgrids, three-phase inverters facilitate the conversion of direct current (DC) generated by renewable sources such as solar panels or wind turbines into alternating current (AC) for use in the grid. This enables the efficient distribution and utilization of renewable energy within the microgrid. In smart grids, three-phase inverters are crucial for maintaining stability and balance in the grid by allowing for bidirectional flow of power between the grid and distributed energy resources [3-4]. Furthermore, three-phase inverters also enable advanced control and monitoring capabilities, making them vital for the successful implementation of smart grid technologies. Thus, the significance of three-phase inverters in microgrids and smart grids cannot be overstated, as they are integral in the advancement towards a more sustainable and efficient energy system [5-7].

Parallel-connected three-phase inverters have gained significant attention in recent years due to their numerous advantages over single-phase inverters, such as increased power capacity, improved efficiency, and enhanced power quality [8]. This configuration involves connecting multiple three-phase inverters in parallel, resulting in a higher total power output. As a result, it has become a popular solution for high-power applications, including renewable energy systems, electric vehicle charging, and industrial motor drives [9-10]. In this arrangement, each inverter is controlled individually and works together in a coordinated manner to supply power to the load. Extensive research has been conducted to explore various control strategies and operating modes for parallel three-phase inverters, with the aim of maximizing their performance and reliability. This has led to the development of novel techniques such as droop control, virtual impedance, and active power sharing methods. The use of parallel-connected three-phase inverters is expected to continue growing in the future, as they offer a promising solution for meeting the increasing demand for high-power, clean, and efficient energy systems [11-13].

Islanded and grid-connected modes refer to two distinct operational states of a power system. In the islanded mode, the system is disconnected from the larger grid and operates independently, relying

solely on its own generation and distribution resources. This mode is typically used in remote or isolated areas where access to the larger grid is not feasible. On the other hand, in the grid-connected mode, the system is connected to a larger network of power generation and distribution, allowing for the exchange of electricity between different regions. This mode is commonly used in urban and densely populated areas to meet the high demand for electricity [14-16]. The transition between these modes can be triggered by various factors such as power outages, changes in demand, or deliberate isolation for maintenance purposes. Understanding the dynamics and characteristics of these two modes is crucial for efficient and reliable operation of modern power systems [17-18].

In recent years, the use of inverters has become increasingly prevalent in various industrial and residential applications due to their efficient and versatile operation. However, the excessive current drawn by these devices can result in various adverse consequences such as overheating, voltage drops, and even system failure. To address these issues, implementing current-limiting methods in inverter control has gained significant attention from researchers and industry professionals. These methods work by regulating the current flow within safe limits, thereby preventing damage to the inverter and associated components [19-20]. Neglecting to incorporate current-limiting methods can not only lead to immediate consequences but also have long-term implications such as reduced lifespan and increased maintenance costs. Therefore, it is crucial to consider and implement appropriate current-limiting techniques in inverter control to ensure the safe and efficient operation of these devices [21].

The management of DC-link voltage control plays a crucial role in the operation of parallel-connected three-phase inverters in microgrid systems. To ensure the reliable and efficient performance of these inverters and the overall microgrid, it is essential to realize the control of the DC link voltage. This voltage serves as the primary source of power for the inverters, which then convert it into AC power for distribution to the connected loads. Any variations or asymmetries in the DC link voltage can result in disruptions and instabilities within the microgrid network, potentially leading to system failures. Therefore, the implementation of a robust and effective DC link voltage control

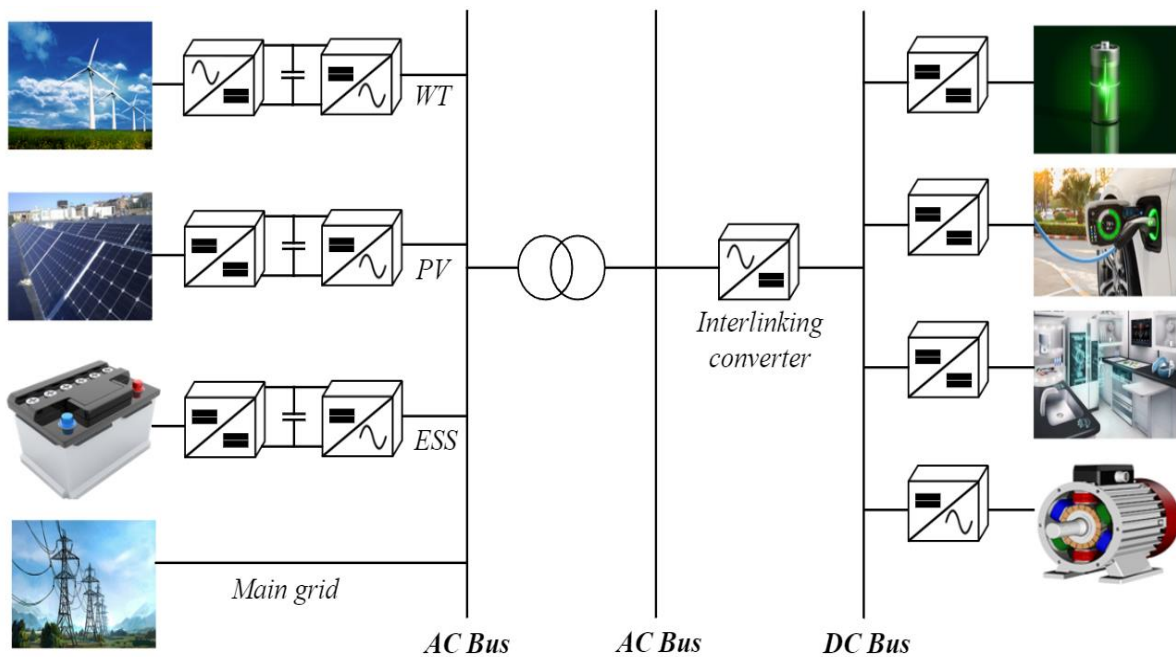


Figure 1. A modern microgrid (Modern bir mikro şebeke)

strategy is imperative for maintaining stable operation and optimal power quality in microgrids. Incorporating such control mechanisms will not only enhance the performance and longevity of the inverters, but also contribute towards the seamless integration of renewable energy sources and efficient energy management within microgrid systems [22-23].

Fault ride-through (FRT) capability has become a crucial aspect of grid-connected systems in recent years. This capability refers to the ability of a system to withstand and continue operating during faults in the electrical grid. The significance of FRT lies in its role in ensuring grid stability and reliability. In the modern electric power systems with high penetration of renewable energy sources, FRT capability has become even more important due to their intermittent nature. A lack of FRT capability can result in voltage dips, system instabilities, and ultimately lead to power outages. Therefore, it is indispensable for grid-connected systems to be equipped with robust FRT capability to achieve secure and stable operation. Moreover, with the increasing integration of distributed energy resources (DERs) in the grid, the importance of FRT has only amplified, as these systems can not only cause faults but are also vulnerable to them. Hence, from a professional and academic perspective, it is necessary to understand and investigate FRT in grid-connected systems to ensure the smooth and reliable operation of the power grid [24-26].

The primary objectives of this study are to address the challenges associated with direct current (DC)

link voltage control and dq-axis current limitation in microgrid systems that consist of multiple parallel-connected three-phase inverters and to tackle the issues that arise during grid voltage sags and the critical transitions between grid-connected and islanded modes.

To address the shortcomings of existing control techniques, particularly those described in [27], an in-depth evaluation of conventional strategies is conducted, and an enhanced control scheme is proposed. The proposed method combines a lead compensator-like structure for stabilizing the DC-link voltage and a saturation-based current limitation approach for managing AC-side dq inverter currents to overcome the existing problems and strengthen microgrid stability and efficiency during mode changes and grid disturbances. This study aims to bridge the gaps in the current literature by identifying the limitations of current methodologies and presenting an improved solution to enhance microgrid resilience and efficiency. The motivation for this research stems from the need for improved fault-ride-through (FRT) capabilities and smoother transitions between different operational states of microgrids. With extensive simulation studies, the effectiveness of the proposed strategy is thoroughly evaluated, its potentials in reducing DC-link voltage fluctuations and dq-axis current surges are demonstrated, thereby minimizing the risk of triggering protection relays. To this end, this research contributes significantly to the advancement of microgrid technologies, paving the way for a more secure, resilient, and optimized energy framework.

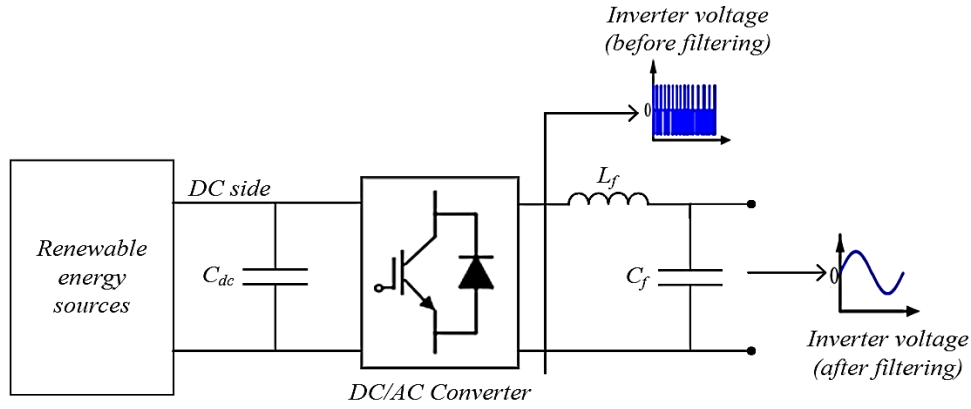


Figure 2. General structure of an inverter (Bir eviricinin genel yapısı)

2. OVERVIEW OF MICROGRIDS AND INVERTERS (EVİRİCİLER VE MİKRO ŞEBEKELERE GENEL BAKIŞ)

Microgrids are small-scale localized energy systems that can operate independently or in conjunction with the larger power grid. They typically consist of locally connected power sources, such as solar panels (PV), wind turbines (WT), and energy storage (ESS) devices, as well as distribution networks for delivering electricity to nearby buildings or communities as provided in Figure 1. Microgrids have gained significant attention in the industrial sector due to their potential to improve energy efficiency, reliability, and resilience. They also offer the flexibility to incorporate renewable energy sources and promote sustainable energy practices. The industrial use of microgrids has become increasingly prevalent in remote or isolated areas where connecting to the main grid may not be feasible or economically viable [28-29]. Additionally, they are being utilized in industrial settings, such as universities, hospitals, and military bases, to reduce energy costs and minimize the risk of power outages. Research in this field has led to the development of advanced control and optimization strategies to improve the performance of microgrids and enhance their integration with the overall power grid [30-31]. Inverters are electronic devices that convert direct current (DC) electricity into alternating current (AC) electricity as illustrated in Figure 2. They play a crucial role in modern industrial applications, where AC electricity is the preferred form of energy due to its high efficiency and ease of transmission over long distances. In addition to their use in industries such as manufacturing, transportation, and telecommunications, inverters are also utilized in the renewable energy sector, where they are essential components in solar and wind power systems. Furthermore, they are widely used in household and commercial settings to power

various electronic devices. Inverters have evolved over the years, with advancements in technology leading to the development of more efficient and reliable models that can meet the growing demands of the industrial sector. As a result, they have become an integral part of modern industrial infrastructure, contributing significantly to the efficient and sustainable production and distribution of energy [32].

3. SYSTEM MODELING AND NECESSARY DEFINITIONS (SİSTEM MODELLENMESİ VE GEREKLİ TANIMLAMALAR)

The study focuses on a microgrid configuration comprising three three-phase inverters operating in parallel, each connected to distinct loads and a common coupling point (PCC) through L filters and transmission lines, as illustrated in Figure 3. This configuration mirrors the setup described in [27], with the addition of considering the grid interface to examine grid-connected (GC) operations, fault ride through capability and mode transitions. The filters' inherent resistance and inductance are labeled as R_f and L_f , respectively, the inductance and resistance of the lines connecting the inverters are identified as $L_{L1}, L_{L2}, R_{L1}, R_{L2}$, respectively. The loads connected to each inverter are represented as resistive elements $R_{Load 1}, R_{Load 2}$, and $R_{Load 3}$. The transmission line linking the PCC to the main grid is characterized by a resistance R_g and an inductance L_g , with the grid-side phase voltages denoted as v_{ga}, v_{gb} , and v_{gc} . The DC components of the inverters consist of a DC source, a diode, and a capacitor (C_{dc}) following the model utilized in [33]. Voltages at the inverter common frame are presented as V_{Ai}, V_{Bi} , and V_{Ci} , where i indicates the

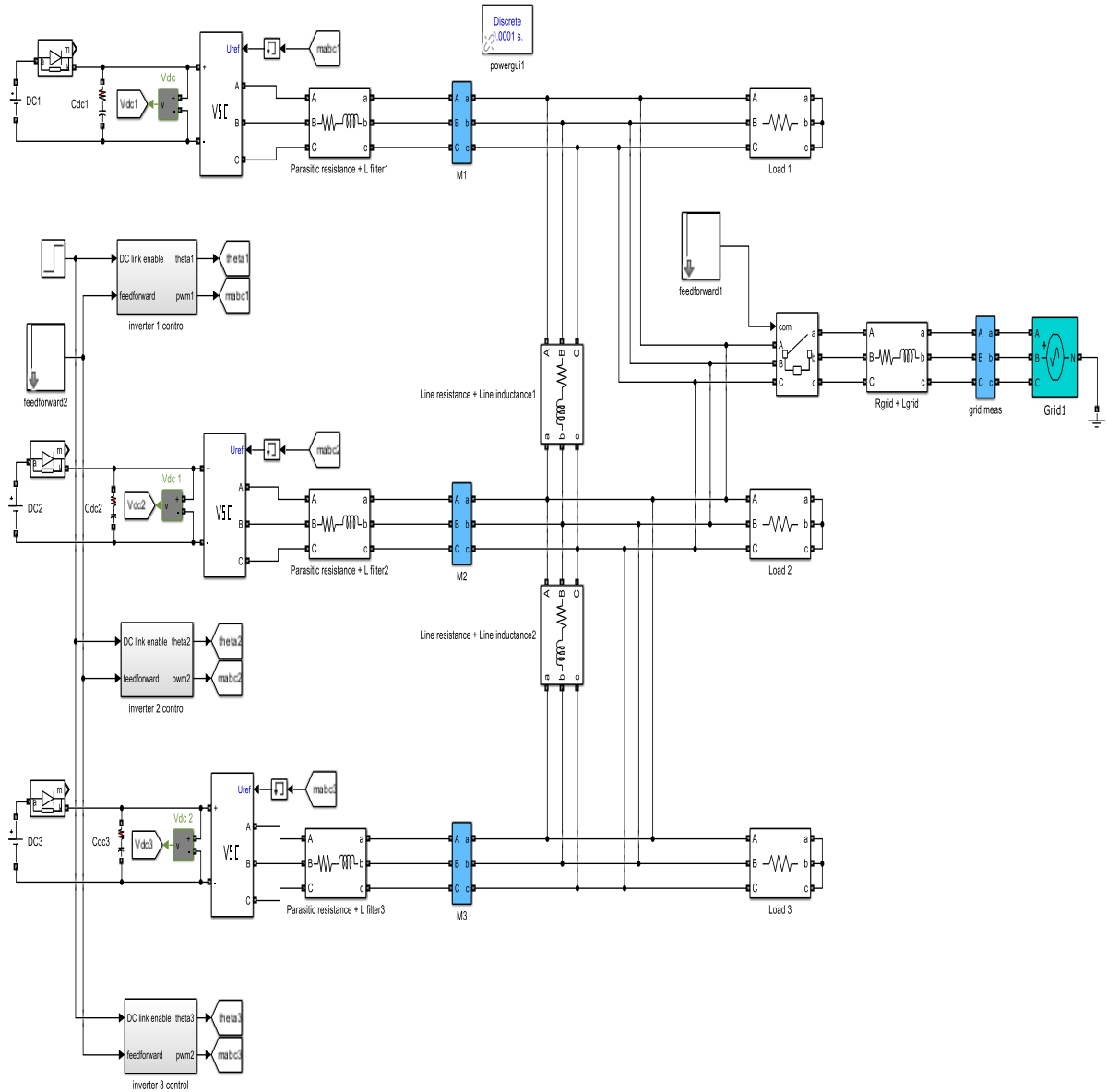


Figure 3. MATLAB/Simulink model of parallel-connected inverter system (Paralel bağlı evirici sisteminin MATLAB/Simulink modeli)

specific inverter. Adapting the approach from [27], the dq voltages at each inverter's local frame are calculated using

$$\begin{bmatrix} V_{dqi} \\ V_{qdi} \end{bmatrix} = \begin{bmatrix} V_{Di} \cos \delta_i + V_{Qi} \sin \delta_i \\ -V_{Di} \sin \delta_i + V_{Qi} \cos \delta_i \end{bmatrix}, \quad (1)$$

where $\delta_i = \theta_i - \theta_{com}$ represents the phase angle deviation between the inverter and the common point. Consequently, the dynamic equations for the inverters in the local dq frame are detailed as below

$$\begin{aligned} L_f \frac{di_{di}}{dt} &= -R_{fi} i_{di} + \omega_i L_{fi} i_{qi} - V_{dqi} + V_{di} \\ L_f \frac{di_{qi}}{dt} &= -R_{fi} i_{qi} - \omega_i L_{fi} i_{di} - V_{qdi} + V_{qi}. \end{aligned} \quad (2)$$

In the context of the described microgrid system, the currents and voltages in the local dq frame of the

inverters are symbolized by i_{di}, i_{qi} and V_{di}, V_{qi} , respectively, with $\omega_i = \dot{\theta}_i$ indicating the inverter's angular frequency. Utilizing equation (1) alongside the inverter's local frame currents, the expressions for calculating the active and reactive power of each inverter emerge as:

$$\begin{aligned} P_i &= \frac{3}{2} [\cos \delta_i (V_{Di} i_{di} + V_{Qi} i_{qi}) + \sin \delta_i (V_{Qi} i_{di} - V_{Di} i_{qi})] \\ Q_i &= \frac{3}{2} [\cos \delta_i (V_{Qi} i_{di} - V_{Di} i_{qi}) - \sin \delta_i (V_{Di} i_{di} + V_{Qi} i_{qi})] \end{aligned} \quad (3)$$

These power equations are integral for understanding the dynamics of power distribution within the microgrid, highlighting the dependency of active and reactive power on the phase angle

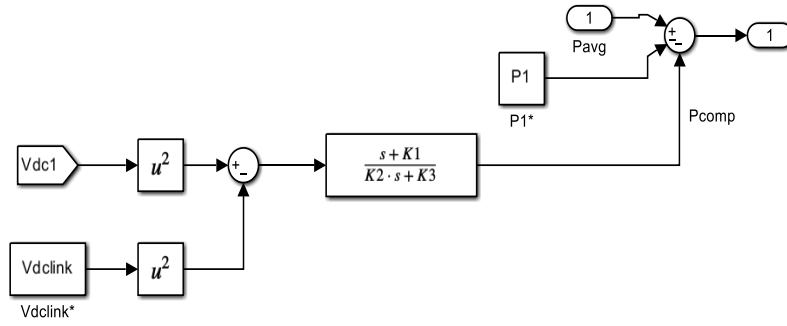


Figure 4. Proposed lead compensator like DC-link controller (Önerilen lead kompanzator benzeri DC-link kontrolör)

difference (δ_i) and the interplay between voltage and current components in the dq frame. Given the importance of maintaining stable operations and managing power distribution effectively, especially during significant faults or mode transitions, the establishment of a control mechanism that ensures the stability of DC-link voltage and limitation of current for each inverter is critical. The proposed approach aims to maintain the operational integrity of the microgrid without exploring the complexities introduced by nonlinearities (3) in the system.

4. PROPOSED DC-LINK CONTROLLER WITH EMBEDDED CURRENT LIMITATION (ÖNERİLEN AKIM LİMİTLEMELİ DC-LINK KONTROLÖR)

In a microgrid, which consists of several parallel-connected inverters, power imbalances and uneven load distribution among the inverters can result in undesired power transfer from high-power to low-power inverters. This could lead to a notable increase in the DC voltage of the low-power inverters, potentially causing harm to the system components or triggering safety mechanisms as mentioned in [27]. Additionally, in practical microgrid applications, it is essential to ensure system stability during various scenarios, such as transitions between islanded and grid-connected modes and grid voltage dips. While [27] has proposed a DC-link controller for an islanded microgrid, it does not consider the impact of these scenarios on the DC-link voltage and the system's dq-axis currents. Therefore, the main objective of this paper is to present a DC-link controller with an integrated current-limiting function to ensure stable and secure operation throughout the microgrid's operation.

In this part, the design and application procedure of a lead compensator like DC-link controller for the

multi-inverter microgrid model, which is given in Figure 3, will be discussed. The proposed controller is embedded to the active power/frequency (P/f) droop control as given in (4)-(5).

$$P_{comp_i} = \left(\frac{s+K_1}{K_2s+K_3} \right) (V_{DClink_i}^2 - V_{DClink}^{*2}) \quad (4)$$

$$\omega_i = \omega_o - m_{pi}(P_{avgi} - P_{comp_i} - P_i^*) \quad (5)$$

$$V_{di} = V_o - n_q Q_i, \quad V_{qi} = 0 \quad (6)$$

Within the framework of the controller provided in (4) and the droop equations presented as (5) and (6), the letter i indicates the individual inverter number, P_{comp_i} denotes the power allocated for compensation, which is integrated into the P/f droop equation. V_{DClink_i} denotes the DC-link voltage for each individual inverter, while V_{DClink}^* refers to the standard DC-link voltage. The gains K_1 , K_2 , and K_3 are identified as the gains associated with the proposed controller. Furthermore, ω_i represents the angular frequency of each inverter, with ω_o indicating the nominal angular frequency. The term m_{pi} is defined as the frequency droop coefficient, P_{avgi} accounts for the average power, which is the power output of each inverter post-application of a low pass filter, and P_i^* is the active power set point designated for each inverter. Additionally, in the context of the reactive power/voltage (Q/V) droop equation (6), V_o and n_q are employed to represent the voltage set point and the voltage droop coefficient, respectively. This framework explains the relationships between controller dynamics and droop mechanisms in regulating power distribution and maintaining system stability across individual inverters within a microgrid configuration. The schematic representation of the proposed compensator is provided in Figure 4.

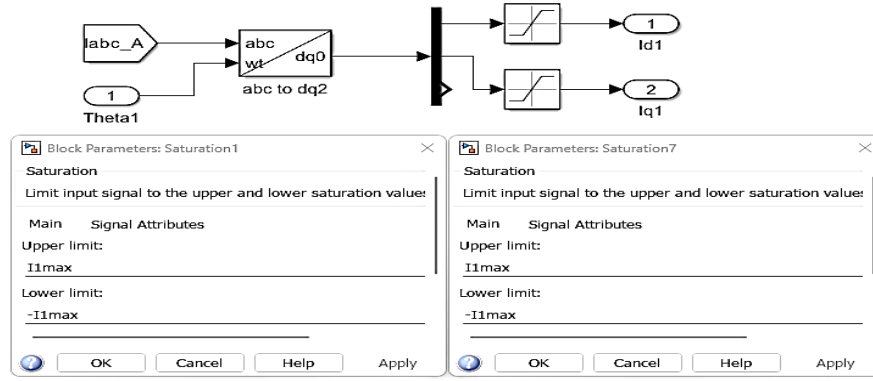


Figure 5. The adopted current limitation method (Kullanılan akım sınırlama yöntemi)

While the controller introduced in this study shares resemblance to the one described in reference [34], which focuses on the application to a singular inverter without detailed examination of the DC-side, the present proposal distinguishes itself through several innovative aspects tailored to microgrid applications. Specifically, this novel controller adopts a structure similar to a lead compensator, diverging significantly in its comprehensive integration with droop control equations, its applicability across various operational modes of the microgrid (including islanded operation, mode transitions, and grid-connected scenarios), and its implementation of a current limitation strategy. These distinctions emphasize the controller's unique contribution to enhancing microgrid performance by addressing the dynamic challenges inherent in multiple system states and ensuring stable, efficient operation through advanced control mechanisms. The emphasis on DC-link controller with droop control integration and current limitation method, in particular, highlights the controller's impact in managing power distribution and stability across the microgrid's different operational conditions.

The current limitation strategy employed within the proposed methodology utilizes an approach that individually saturates the d and q axis currents, as explained in [21]. For a comprehensive understanding of this technique, readers are encouraged to consult [21]. Figure 5 shows a schematic representation of the current-limiting method as implemented, providing a visual aid to better understand the mechanics behind this approach. This technique is integral to ensuring the proposed controller's effectiveness in maintaining

the system stability and performance by managing current flows within the microgrid infrastructure.

Both d and q axis current limits are given as I_{imax} and they can be calculated as [21]

$$I_{imax} = 1.2 * \sqrt{2} * P_i / (3 * V_{rms}^*) \quad (7)$$

P_i is the power rating of the individual inverters and V_{rms}^* is the rated root mean square (RMS) voltage.

5. SIMULATION AND COMPARISON STUDIES (SİMÜLASYON VE KARŞILAŞTIRMA ÇALIŞMALARI)

The effectiveness of the proposed DC-link controller was evaluated in this study by constructing a microgrid configuration with three parallel-connected three-phase inverters as given in Figure 3, as per [27], within Matlab/Simulink environment. In contrast to [27], which exclusively focused on standalone (SA) inverter functionality without addressing current limitations, the current study expands the analysis to involve both grid-connected (GC) scenarios and transitions between SA and GC modes. The specific parameters utilized for the simulated system and controllers for both proposed and comparison [27] systems are detailed in Table I. In the simulation studies, the performance of the proposed controller is displayed on the left-hand side (LHS) of Figures 6-10, while the performance of the existing system [27] is shown on the right-hand side (RHS).

The simulation is initiated in islanded mode, with the isolation switch open, at $t=0s$. The system quickly reaches steady-state conditions, as indicated by the stable behavior observed in Figures 6 and 7. Furthermore, there are no instances of overcurrent, as shown in the left-hand side of Figures 8, 9, and

Table 1. System and controller simulation parameters used in comparison studies (Karşılaştırma çalışmalarında kullanılan sistem ve kontrolör simülasyon parametreleri)

Parameters	Values	Parameters	Values	Parameters	Values
P_1^*	20 kW	P_2^*	10 kW	P_3^*	0 kW
$R_{Load 1}$	25Ω	$R_{Load 2}$	20Ω	$R_{Load 3}$	38Ω
L_{fi}	2mH	R_{fi}	0.1Ω	n	0.001
m_i	1.0472×10^{-4}	V_{rms}^*	220 V	f^*	50 Hz
V_{dclink}^*	750 V	R_{Line1}	0.23Ω	L_{Line1}	0.32mH
R_{Line2}	0.35Ω	L_{Line2}	1.85mH	C_{dc}	1.1mF
K_1	180	K_2	0.1	K_3	400
k_p	30	k_d	1	T_s	10^{-4}
ω_o	$2\pi f^*$	R_g	0.5Ω	L_g	2.2mH
I_{1max}	51.43 A	I_{2max}	25.71 A	I_{3max}	0 A

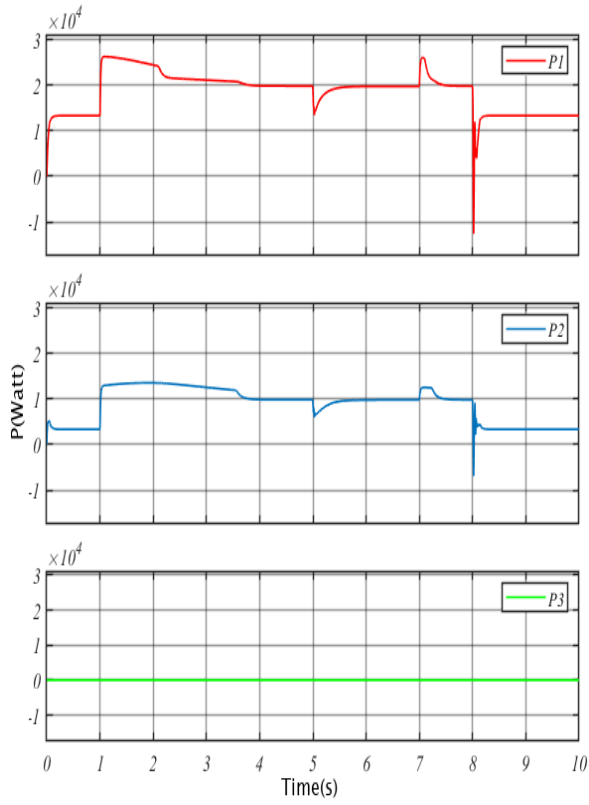
10. At $t=1s$, a seamless transition from SA to GC mode is achieved by closing the isolation switch. This transition does not cause any instability or current limit violation, as evidenced by the data presented in Figures 6-10. However, the existing approach leads to significant peaks in the active powers, DC voltages, d and q axis currents, which may result in protection relay triggers or damage to system components.

At $t=5s$, a 20% decrease in grid voltage is implemented as a means of evaluating the effectiveness of the controller in handling faulty conditions. Despite the severity of the situation, the controller successfully manages the regulation of the DC-link voltage, thereby maintaining the stability of the system. This is demonstrated in Figures 7-10. The temporary fluctuations in the DC-link voltages of the inverters, as shown in Figure 7, fall within acceptable limits [27], highlighting the system's capability to tolerate minor deviations.

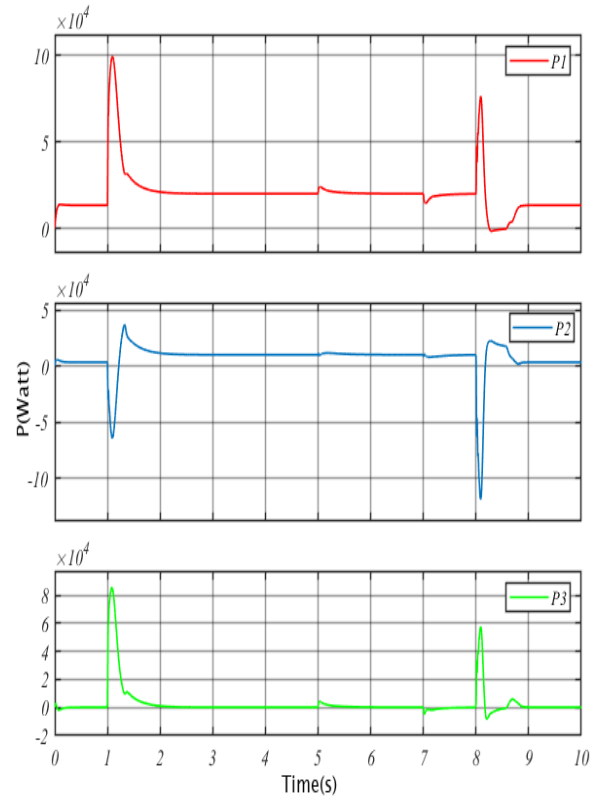
At $t=7s$, the grid voltage was restored, resulting in the system reverting to the SA mode at $t=8s$. This transition was successfully managed by the proposed method without any violation, effectively demonstrating its ability to handle normal and faulty operations without causing overcurrent or DC-link voltage issues. However, it should be noted that the

existing method [27] lacks the capability to limit the DC-link voltages and d and q inverter currents. The simulation ends at $t=10s$.

A comparative analysis was conducted between the controller proposed in this study and an existing method outlined in [27]. Results reveal significant advantages of the proposed controller, particularly in the regulation of DC-link voltage and current limitation, across a variety of operational scenarios. Overall, the proposed controller demonstrates superior performance in managing DC-link voltage and limiting system currents throughout the microgrid's operation. Such improvements are critical in ensuring the reliability and efficiency of microgrids, especially with varying grid conditions.

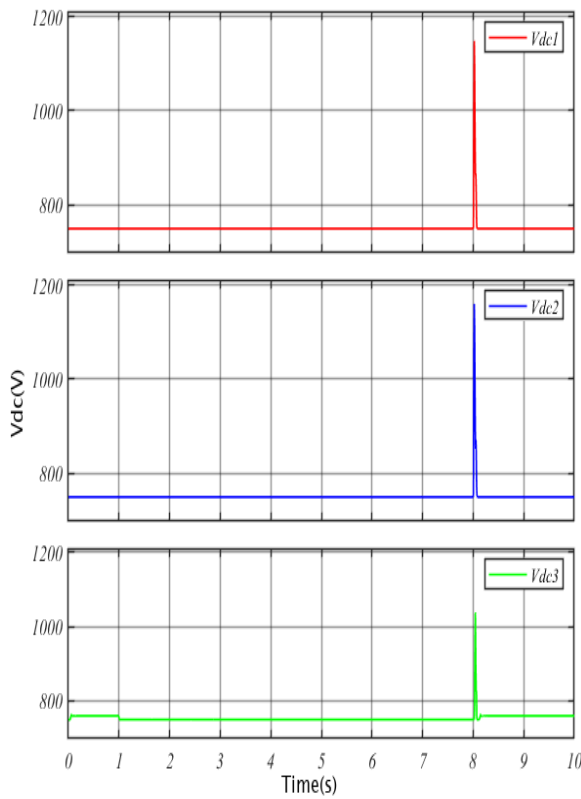


a. Proposed controller (Önerilen kontrolör)

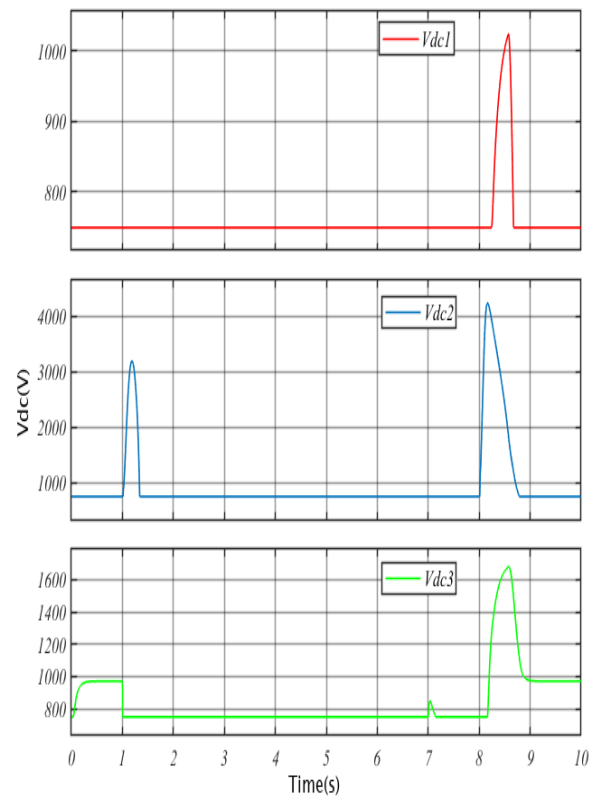


b. Existing controller (Mevcut kontrolör)

Figure 6. Active power outputs of individual inverters (Eviricilerin herbirinin aktif güç çıkışları)

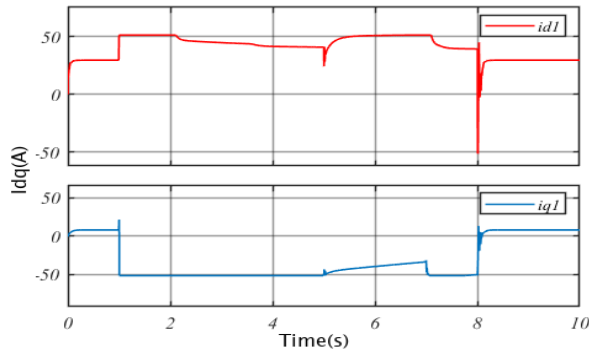


a. Proposed controller (Önerilen kontrolör)

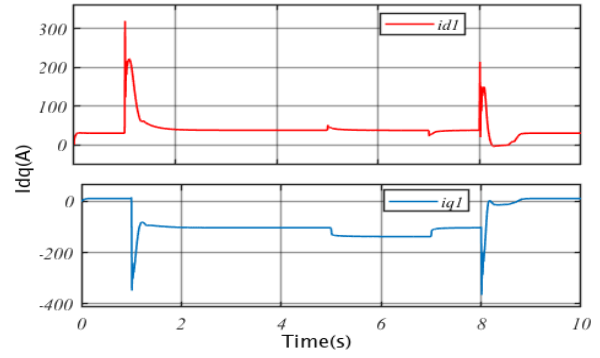


b. Existing controller (Mevcut kontrolör)

Figure 7. DC-link voltages of individual inverters (Eviricilerin herbirinin DC-link voltajları)

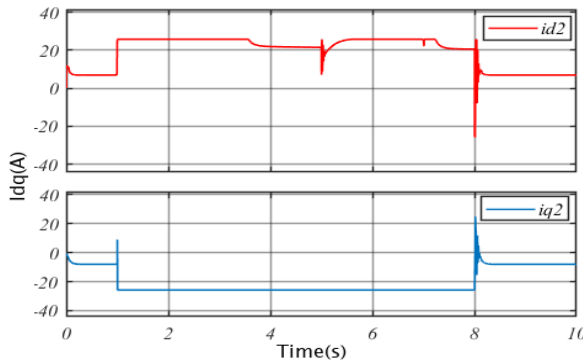


a. Proposed controller (Önerilen kontrolör)

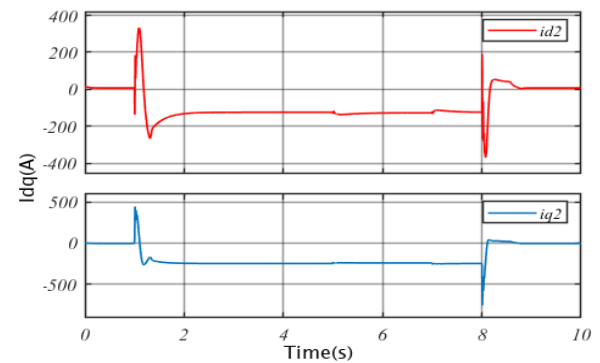


b. Existing controller (Mevcut kontrolör)

Figure 8. d and q axis currents of inverter 1 (1. Eviricinin d ve q eksen akımları)

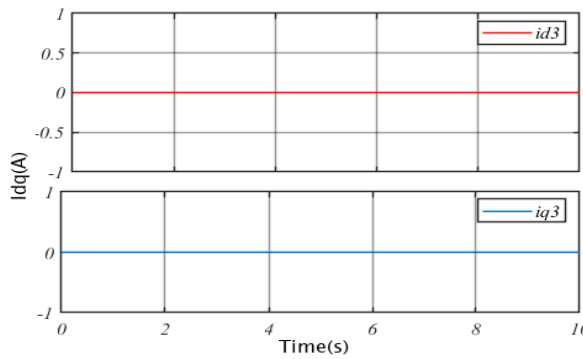


a. Proposed controller (Önerilen kontrolör)

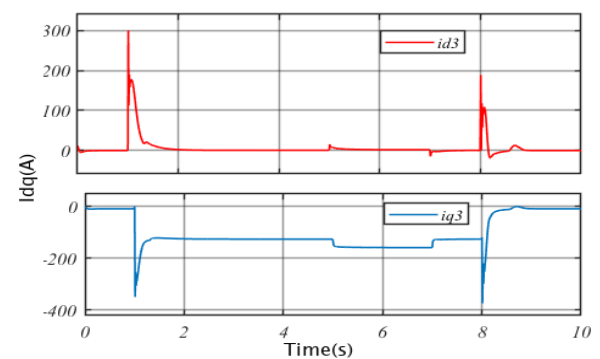


b. Existing controller (Mevcut kontrolör)

Figure 9. d and q axis currents of inverter 2 (2. Eviricinin d ve q eksen akımları)



a. Proposed controller (Önerilen kontrolör)



b. Existing controller (Mevcut kontrolör)

Figure 10. d and q axis currents of inverter 3 (3. Eviricinin d ve q eksen akımları)

6. CONCLUSIONS (SONUÇLAR)

This study aimed to investigate a novel design for an AC microgrid utilizing parallel three-phase inverters. The main focus was to develop a unique controller capable of effectively regulating the DC-link voltage and implementing a current limitation method. This strategy effectively managed the dq-axis currents, ensuring system stability and mitigating abrupt changes in DC-link voltage and currents during grid disruptions and transitions. The simulations conducted using Matlab/Simulink effectively demonstrated the efficiency of the proposed controller in stabilizing the system,

reducing DC-link voltage oscillations, and maintaining dq-axis currents below the rated maximum values for each inverter. The obtained findings clearly illustrated the effectiveness of the proposed methodology in mitigating the undesirable effects of DC-link voltage fluctuations and dq-axis currents during mode transitions in multi-inverter systems. By applying the proposed approach, it was ensured that the specified limits for these parameters are consistently maintained, thereby preventing any potential risk of instability or violations in the system. In contrast, the existing approach demonstrated a tendency to exceed the prescribed limits, emphasizing the superiority of the

proposed methodology in this regard. Hence, the proposed approach can be accepted as a reliable solution for addressing the challenges associated with mode transitions in multi-inverter systems. These improvements significantly reduced the likelihood of triggering protection relays and surpassed the performance of an existing approach. This highlights the potential of the proposed controller to enhance microgrid resilience and

DECLARATION OF ETHICAL STANDARDS
(ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan eder.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

Seyfullah DEDEOĞLU: He conducted the simulations, analyzed the results and performed the writing process.

Simülasyonları yapmış, sonuçlarını analiz etmiş ve makalenin yazım işlemini gerçekleştirmiştir.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

REFERENCES (KAYNAKLAR)

[1] D. Baimel, J. Belikov, J. M. Guerrero and Y. Levron, "Dynamic Modeling of Networks, Microgrids, and Renewable Sources in the dq0 Reference Frame: A Survey," *IEEE Access*, vol. 5, pp. 21323-21335, 2017, doi: 10.1109/ACCESS.2017.2758523.

[2] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. de Vicuna and M. Castilla, "Hierarchical Control of Droop-Controlled AC and DC Microgrids—A General Approach Toward Standardization," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 158-172, Jan. 2011, doi: 10.1109/TIE.2010.2066534.

[3] T. Jin and M. Mechehoul, "Ordering Electricity via Internet and its Potentials for Smart Grid Systems," *IEEE Transactions on Smart Grid*, vol. 1, no. 3, pp. 302-310, Dec. 2010, doi: 10.1109/TSG.2010.2072995.

reliability. To this end, this study not only presented a significant advancement in microgrid control strategies but also provided compelling evidence of the proposed controller's ability to strengthen microgrid stability and operational efficiency. Its adaptability in managing various operational scenarios makes it a valuable tool for future microgrid management.

[4] C. Parthasarathy, Katja Sirviö, H. Hafezi, and H. Laaksonen, "Modelling battery energy storage systems for active network management—coordinated control design and validation," *IET Renewable Power Generation*, vol. 15, no. 11, pp. 2426–2437, Apr. 2021, doi: <https://doi.org/10.1049/rpg2.12174>.

[5] T. Morstyn, B. Hredzak and V. G. Agelidis, "Control Strategies for Microgrids With Distributed Energy Storage Systems: An Overview," *IEEE Transactions on Smart Grid*, vol. 9, no. 4, pp. 3652-3666, July 2018, doi: 10.1109/TSG.2016.2637958.

[6] N. Liu, X. Yu, C. Wang, C. Li, L. Ma and J. Lei, "Energy-Sharing Model With Price-Based Demand Response for Microgrids of Peer-to-Peer Prosumers," *IEEE Transactions on Power Systems*, vol. 32, no. 5, pp. 3569-3583, Sept. 2017, doi: 10.1109/TPWRS.2017.2649558.

[7] L. Wang, D. Zhang, Y. Wang, B. Wu and H. S. Athab, "Power and Voltage Balance Control of a Novel Three-Phase Solid-State Transformer Using Multilevel Cascaded H-Bridge Inverters for Microgrid Applications," *IEEE Transactions on Power Electronics*, vol. 31, no. 4, pp. 3289-3301, April 2016, doi: 10.1109/TPEL.2015.2450756.

[8] J. M. Guerrero, P. C. Loh, T. -L. Lee and M. Chandorkar, "Advanced Control Architectures for Intelligent Microgrids—Part II: Power Quality, Energy Storage, and AC/DC Microgrids," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 4, pp. 1263-1270, April 2013, doi: 10.1109/TIE.2012.2196889.

[9] S. Bella et al., "Circulating Currents Control for Parallel Grid-Connected Three-Phase Inverters," 2018 International Conference on Electrical Sciences and Technologies in Maghreb (CISTEM), Algiers, Algeria, 2018, pp. 1-5, doi: 10.1109/CISTEM.2018.8613377.

[10] Keliang Zhou and Danwei Wang, "Relationship between space-vector modulation and

- three-phase carrier-based PWM: a comprehensive analysis [three-phase inverters]," *IEEE Transactions on Industrial Electronics*, vol. 49, no. 1, pp. 186-196, Feb. 2002, doi: 10.1109/41.982262.
- [11] F. Deng, W. Yao, X. Zhang, Y. Tang and P. Mattavelli, "Review of Impedance-Reshaping-Based Power Sharing Strategies in Islanded AC Microgrids," *IEEE Transactions on Smart Grid*, vol. 14, no. 3, pp. 1692-1707, May 2023, doi: 10.1109/TSG.2022.3208752.
- [12] Y. Han, X. Ning, P. Yang and L. Xu, "Review of Power Sharing, Voltage Restoration and Stabilization Techniques in Hierarchical Controlled DC Microgrids," *IEEE Access*, vol. 7, pp. 149202-149223, 2019, doi: 10.1109/ACCESS.2019.2946706.
- [13] Y. Han, H. Li, P. Shen, E. A. A. Coelho and J. M. Guerrero, "Review of Active and Reactive Power Sharing Strategies in Hierarchical Controlled Microgrids," *IEEE Transactions on Power Electronics*, vol. 32, no. 3, pp. 2427-2451, March 2017, doi: 10.1109/TPEL.2016.2569597.
- [14] X. Hou et al., "Distributed Hierarchical Control of AC Microgrid Operating in Grid-Connected, Islanded and Their Transition Modes," *IEEE Access*, vol. 6, pp. 77388-77401, 2018, doi: 10.1109/ACCESS.2018.2882678.
- [15] Rahul Ranjan Jha, Suresh Chandra Srivastava, and M. Kumar, "Development of control schemes for a cluster of PV-integrated houses in islanded mode," *IET Renewable Power Generation*, vol. 11, no. 7, pp. 903-911, Feb. 2017, doi: <https://doi.org/10.1049/iet-rpg.2016.0048>.
- [16] F. Wu, X. Li, F. Feng and H. B. Gooi, "Multi-topology-Mode Grid-Connected Inverter to Improve Comprehensive Performance of Renewable Energy Source Generation System," *IEEE Transactions on Power Electronics*, vol. 32, no. 5, pp. 3623-3633, May 2017, doi: 10.1109/TPEL.2016.2589974.
- [17] D. Velasco de la Fuente, C. L. Trujillo Rodríguez, G. Garcerá, E. Figueres and R. Ortega Gonzalez, "Photovoltaic Power System With Battery Backup With Grid-Connection and Islanded Operation Capabilities," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 4, pp. 1571-1581, April 2013, doi: 10.1109/TIE.2012.2196011.
- [18] F. Rahimi, A. Ipakchi and F. Fletcher, "The Changing Electrical Landscape: End-to-End Power System Operation Under the Transactive Energy Paradigm," *IEEE Power and Energy Magazine*, vol. 14, no. 3, pp. 52-62, May-June 2016, doi: 10.1109/MPE.2016.2524966.
- [19] X. Lin, Z. Liang, Y. Zheng, Y. Lin and Y. Kang, "A Current Limiting Strategy With Parallel Virtual Impedance for Three-Phase Three-Leg Inverter Under Asymmetrical Short-Circuit Fault to Improve the Controllable Capability of Fault Currents," *IEEE Transactions on Power Electronics*, vol. 34, no. 8, pp. 8138-8149, Aug. 2019, doi: 10.1109/TPEL.2018.2879191.
- [20] I. Sadeghkhan, M. E. Hamedani Golshan, J. M. Guerrero and A. Mehrizi-Sani, "A Current Limiting Strategy to Improve Fault Ride-Through of Inverter Interfaced Autonomous Microgrids," *IEEE Transactions on Smart Grid*, vol. 8, no. 5, pp. 2138-2148, Sept. 2017, doi: 10.1109/TSG.2016.2517201.
- [21] N. Bottrell and T. C. Green, "Comparison of Current-Limiting Strategies During Fault Ride-Through of Inverters to Prevent Latch-Up and Wind-Up," *IEEE Transactions on Power Electronics*, vol. 29, no. 7, pp. 3786-3797, July 2014, doi: 10.1109/TPEL.2013.2279162.
- [22] M. Farrokhhabadi et al., "Microgrid Stability Definitions, Analysis, and Examples," *IEEE Transactions on Power Systems*, vol. 35, no. 1, pp. 13-29, Jan. 2020, doi: 10.1109/TPWRS.2019.2925703.
- [23] Y. Gui, F. Blaabjerg, X. Wang, J. D. Bendtsen, D. Yang and J. Stoustrup, "Improved DC-Link Voltage Regulation Strategy for Grid-Connected Converters," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 6, pp. 4977-4987, June 2021, doi: 10.1109/TIE.2020.2989720.
- [24] S. Xu, Y. Xue and L. Chang, "Review of Power System Support Functions for Inverter-Based Distributed Energy Resources- Standards, Control Algorithms, and Trends," *IEEE Open Journal of Power Electronics*, vol. 2, pp. 88-105, 2021, doi: 10.1109/OJPEL.2021.3056627.
- [25] M. J. Morshed and A. Fekih, "A Novel Fault Ride Through Scheme for Hybrid Wind/PV Power Generation Systems," *IEEE Transactions on*

- Sustainable Energy, vol. 11, no. 4, pp. 2427-2436, Oct. 2020, doi: 10.1109/TSTE.2019.2958918.
- [26] Y. Wang and B. Ren, "Fault Ride-Through Enhancement for Grid-Tied PV Systems With Robust Control," IEEE Transactions on Industrial Electronics, vol. 65, no. 3, pp. 2302-2312, March 2018, doi: 10.1109/TIE.2017.2740858.
- [27] W. Issa, Faris Al-naemi, G. Konstantopoulos, Sulieman Sharkh, and M. Abusara, "Stability Analysis and Control of a Microgrid against Circulating Power between Parallel Inverters," Energy Procedia, vol. 157, pp. 1061-1070, Jan. 2019, doi: <https://doi.org/10.1016/j.egypro.2018.11.273>.
- [28] A. Qazi et al., "Towards Sustainable Energy: A Systematic Review of Renewable Energy Sources, Technologies, and Public Opinions," IEEE Access, vol. 7, pp. 63837-63851, 2019, doi: 10.1109/ACCESS.2019.2906402.
- [29] S. Parhizi, H. Lotfi, A. Khodaei and S. Bahramirad, "State of the Art in Research on Microgrids: A Review," IEEE Access, vol. 3, pp. 890-925, 2015, doi: 10.1109/ACCESS.2015.2443119.
- [30] F. Nejabatkhah, Y. W. Li and H. Tian, "Power Quality Control of Smart Hybrid AC/DC Microgrids: An Overview," IEEE Access, vol. 7, pp. 52295-52318, 2019, doi: 10.1109/ACCESS.2019.2912376.
- [31] P. G. Arul, Vigna Kumaran Ramachandaramurthy, and R. K. Rajkumar, "Control strategies for a hybrid renewable energy system: A review," Renewable & Sustainable Energy Reviews, vol. 42, pp. 597-608, Feb. 2015, doi: <https://doi.org/10.1016/j.rser.2014.10.062>.
- [32] R. Domínguez, A. J. Conejo and M. Carrión, "Toward Fully Renewable Electric Energy Systems," IEEE Transactions on Power Systems, vol. 30, no. 1, pp. 316-326, Jan. 2015, doi: 10.1109/TPWRS.2014.2322909.
- [33] W. R. Issa, M. A. Abusara and S. M. Sharkh, "Control of Transient Power During Unintentional Islanding of Microgrids," IEEE Transactions on Power Electronics, vol. 30, no. 8, pp. 4573-4584, Aug. 2015, doi: 10.1109/TPEL.2014.2359792.
- [34] L. Huang et al., "A Virtual Synchronous Control for Voltage-Source Converters Utilizing Dynamics of DC-Link Capacitor to Realize Self-Synchronization," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 5, no. 4, pp. 1565-1577, Dec. 2017, doi: 10.1109/JESTPE.2017.2740424.