JOURNAL OF SCIENCE, TECHNOLOGY AND ENGINEERING RESEARCH
Bilim, Teknoloji ve Mühendislik Araştırmaları Dergisi
ISSN (Online) 2717-8404
Available *online* at https://dergipark.org.tr/en/pub/jster

REVIEW ARTICLE

Review of Grid-Connected Solar PV Systems With Decoupled Control

[*] Abdulkadir OZCAN, [1]Ahmed Saadoon ALGBURI, [2]Omar Ali NUAIMI, [3] Hanaa Hussein LAFTA

[*]College of Engineering and Natural Sciences, Department of Electrical Electronics Engineering, KTO Karatay University, Konya, Turkey
abdulkadir.ozcan@karatay.edu.tr, Orcid. 0009-0009-7224-1798

[1]Department Electrical-Computer Engineering, College of Engineering, University of KTO Karatay University, Konya, Turkey
Eng.ahmet.shkur@gmail.com, Orcid. 0009-0006-0969-6878
[2]Department of Electrical - Electronic Engineering, college of Engineering, Istanbul Gelisim University, Istanbul, Turkey
Omar.ali.khaleel1@gmail.com , Orcid. 0009-0004-2210-0931
[3]Department of Mechatronics Engineering, College of Engineering, University of KTO Karatay University, Konya, Turkey
Hanaa.hussein.lafta@gmail.com, Orcid. 0009-0001-1838-1951

Citation:
Özcan, A., Algburi, A.S., Nuaimi, O.A., Lafta H.H, (2024). *Review of Grid-Connected Solar PV Systems With Decoupled Control*, Journal of Science Technology and Engineering Research, 5(2): 135-147. DOI: 10.53525/jster.1533727

HIGHLIGHTS

- *Filling knowledge gaps in optimizing power management in renewable energy systems.*
- *Exploring methods like vector control, direct power control, and model predictive control.*
- *By showcasing the importance of decoupled control, it emphasizes solutions for stabilizing power flows in modern grids*
- *Enhanced understanding of active/reactive power decoupling methods.*

Article Info

Received : 15 August 2024
Accepted : 14 November 2024

DOI:
10.53525/jster.1533727

***Corresponding Author:**

Abdulkadir OZCAN
abdulkadir.ozcan@karatay.edu.tr
Phone: +90 555 878 88 76

ABSTRACT

This paper presents a decoupled control for grid-connected solar photovoltaic (PV) system. The control framework used in this paper aims not to track the changing maximum power point (MPP) for extracting power at MPP, hence blocking the MPP tracking issue against the effect of solar radiation and temperature. Real power is produced by tracking the control voltage with a zero-dynamics-based controller. A cascaded loop controller with inner loop to regulate the control voltage is incorporated to ensure the produced real power follows the reference power in the presence of power disturbance. The proposed control scheme with the consideration of the inverter's rated voltage shows improved system dynamics. Simulations in various conditions are conducted to prove the effectiveness of the proposed control strategies. CIGRE 13-node benchmark system is used as the case study to evaluate the results of the PV system connected to a more complex power system. It has been shown that the proposed controller allows the total production of the energy under maximum power point conditions and also improves the overall stability of distributed generation connected to the grid. Therefore, it can be implemented to increase the capacity of renewable inverter-based power generation and the power system quality.

Keywords: *solar power, power generation, solar energy, decoupled control*

I. INTRODUCTION

Furthermore, the distribution static compensation (DSTATCOM) and the uninterruptible power supply (UPS) need to be operated during a grid-connected mode and a grid blackout condition while the solar PV system is disconnected from the grid. The energy storage system, such as a battery, a supercapacitor, and a flywheel system, is used for compensating the solar power quality problem by the energy storage system and the DSTATCOM during grid-connected mode and grid overvoltage condition. The energy management system based on the state of charge of the storage system is developed for the storage system efficiency. However, the solar energy system profitability is increased if the battery energy is designed with a better payback period of the investment [1].

The control algorithms are developed for maximum power point tracking and inverter control method for the conventional grid-connected solar PV system. However, in the conventional solar PV system, the solar PV system cannot be operated during a grid blackout condition. On the other hand, the solar PV system should be disconnected from the grid when the grid voltage is over the specified operating range. Because the solar PV system cannot supply the load, the disconnection of the solar PV system from the grid is used for voltage and frequency regulation in one-second control in autonomous mode or grid-connected mode [2].

To improve the efficiency of the solar power generation system and reduce the cost of the system, many research have been done in power electronic devices, control algorithms, and the configuration of the power conversion circuit connected between the solar PV system and the grid. In the conventional solar PV system, the control algorithms are developed for a maximum power point tracking method and a unity power factor operation of the inverter via a direct power control method to improve the efficiency of the solar PV system [3].

The solar power generation system is one of the promising sources of renewable energy. Nowadays, the solar photovoltaic (PV) system is the most attractive power generation source because it generates power at the point of usage, has high reliability, low maintenance cost, and a reasonable payback time. The solar power generation also has self-consumption and self-dispatch characteristics. These characteristics can be supported for stabilizing grid instability due to intermittent power generation by the self-consumption of solar power [1].

II. FUNDAMENTALS OF SOLAR PHOTOVOLTAIC SYSTEMS INTRODUCTION

An inverter is a power electronic device, converting DC to AC. The conversion is typically accomplished by the boost inverter, voltage source inverter, current source inverter, and multilevel inverter. A pure sine wave output of an inverter is the achievement. These inverters have two output filters, in which the presence of separate control is allowed so that the power can be distributed by a given mode. In grid-connected SPV systems, a multimode inverter can define the different functions that can contribute [4]. To make the consumption of energy easy, other functionalities such as filtering, reactive power compensation, and Ride Through Mode are viewed by the multimode inverter. In the absence of a power connection, a standalone system can also be running. The inverter multimode is driven CE, PE, and ES, to express the association. A functional enhancement of the grid allows the presence of other functionalities, CE, and PE. In the case of a strategy, the top level of the inverter deserves a certain strategy. The PV device allows a constant DC card to be sent to the motor drive in the output [5]. Moreover, after step-up connected by a DC-DC, the photovoltaic system at the other end is constructed. Finally, the connected switch is a DC-DC converter, to charge the battery or indeed support the grid to stabilize [6].

PV photovoltaic systems can generally be classified into three different types, i.e., standalone PV systems, grid-connected PV systems, and hybrid PV systems. In standalone PV systems, solar PV modules usually supply power to DC loads, and DC loads sometimes convert to AC loads by using an inverter. The charging of the battery is carried out by the PV system after the loads are satisfied [7]. The inverter supplies the AC supply to the AC loads. In grid-connected PV systems, the power is used not only by the loads, but the excess power is fed back to the grid. In hybrid PV systems, it is the combination of standalone PV systems and grid-connected PV systems. It is a good form of electrification in underdeveloped, distant areas and largely isolated from the national grid. They provide electricity by means of renewable energy sources, and the power is stored in the battery for a 24-hour power supply. In this work, grid-connected PV systems and DC-coupled solar PV generate a constant DC voltage for a battery bank at the load. This is followed by the AC grid, offering power support [8]. Another output from the multimode inverter is fed into the traction motor through an LC filter circuit, converting the DC power to the AC source required to run the traction [9].

As the energy demand is rapidly increasing, researchers are looking for eco-friendly, renewable energy sources such as hydropower, solar energy, wind, and biogas. Among these sources, solar energy is one of the most promising sources because of its abundance and free availability [10]. There are two types of solar power systems: solar photovoltaic and solar thermal systems. Solar cells are the basic building block of a solar photovoltaic system. Solar PV systems have advantages of silent operation, low maintenance cost, low payback period, fast installation, and no carbon emissions. Efficiencies and cost per KW of solar PV systems have been rapidly improved. Most of the modern technologies for infrared generation are based on photonic processes, for instance, incandescent, fluorescent, and light-emitting diodes [11].

A. Basic Principle of Solar Pv Systems

The sun is the ultimate source of energy for our planet. The energy from the sun reaches the earth in two forms: light and heat [12]. The electromagnetic radiation from the sun that reaches the earth is composed of both light and heat, known as thermal radiation. The thermal part of the radiation is absorbed by the atmosphere, and the light part is incident on the earth's surface [13]. However, it should be noted that heat is responsible for the greenhouse effect. The light incident on the earth's surface is the necessary element for the photosynthesis process in plants [14].

With the increase in power demand and depletion of fossil fuels, photovoltaic (PV) power generation is gaining substantial attention and is one of several promising alternate sources of energy. A solar photovoltaic system harnesses solar energy through PV modules to generate electricity in the form of DC power [15]. The generated DC power is later used as is or converted into AC power using an inverter. Conversion of electrical energy from sunlight can provide significant benefits to society, both in reducing environmental pollution and enhancing energy security for a nation [16].

B. Types of Solar Pv Systems

The implementation of grid-connected photovoltaic (GCPV) systems for renewable energy has been rising. GCPV systems are clean, quiet, and have many other advantages. Also, it is easy for a GCPV system to be downscaled or upscaled in size, making it very flexible in its application. As an inverter is a very important device for GCPV systems, grid-connected inverters must have the most advanced technology for inverting DC power into AC power [17]. An efficient inverter is capable of greatly increasing the amount of power that is injected into the grid. When the phase-locked loop (PLL) performs its task, it uses a Pure Generalized Integrator (PGI) to increase its speed. When the grid frequency suddenly changes, the PLL synchronizes with the grid frequency. With traditional GCPV systems, the electronic interface contains two DC-DC converters, and the voltage used to feed the inverter-aligned voltage bus structure. This kind of process causes voltage increases. It is harder to control the interface to stabilize the voltage without power regulation [18].

III. GRID-CONNECTED SOLAR PV SYSTEMS

Solar irradiance typically ranges from about 1361 to 1362 W/m² at the top of Earth's atmosphere (known as the solar constant) under Air Mass 0 (AM0) conditions. However, at ground level, under clear sky conditions and Air Mass

1.5 (AM1.5), which is commonly used for photovoltaic testing, the irradiance usually does not exceed 1000 W/m², while the operating temperature of solar PV panels changes in the range of 15–65 °C. This wide range of fluctuation offers a particularly complicated problem in the design of the controller. Maximum power must be tracked to overcome the solar irradiation unit and temperature, even during partial shades or quick changes in operating points of the interconnected solar panel [19]. However, to accomplish the proper condition of the solar module, procedures to decouple P (Active power) and Q (Reactive power) are essential. Indeed, solar inverters should not generate reactive power at night, as this can drain the grid network power lines and present power factor problems, potentially damaging a power grid's stability [20].

The output current of solar photovoltaic inverters is associated with solar irradiation. Output voltage relies on solar panel temperature primarily and changes as any dependence on the solar panel transposition line. The inverter should compensate precisely for output variations due to solar radiation and module temperature. The control system must ensure this for maximum energy harvesting [21].

A grid-connected solar PV system employs solar panels to convert sunlight into electricity before feeding it directly into the electricity grid. The system consists of several modules and a power conditioning unit (inverter). In general, a photovoltaic array requires an inverter and feedback with grid voltage to supply power to a three-phase grid-connected inverter [22].

Grid-connected solar photovoltaic (PV) power systems convert light energy directly into electrical energy through the photoelectric effect and the use of a semiconductor material, for example, silicon wafers. Without any disturbance to environmental conditions such as cloud cover, this renewable source can provide useful energy. Large potential exists in most areas globally for the deployment of grid-connected solar photovoltaic systems to supply a significant part of the energy demand with relatively low environmental impact [22].

A. Components of A Grid-Connected Solar Pv System

- Grid-Connected Solar PV System with Decoupled Control
- Filters: The low-frequency harmonics need to be reduced to maintain a high-power quality of the grid-side current and voltage.
- DC-AC Panel Converter: In a solar power plant, large arrays can be built. To avoid shading, mounting, and size-related losses, the array is divided into a set of independent smaller modules. A panel converter can be utilized to convert the modules at the DC end itself [23].
- Inverter: It converts the DC power from the solar PV array to a precisely defined AC power output form suitable for interfacing with the utility grid [24].
- DC-DC Boost Converter: It boosts the DC power generated by the solar PV array to the DC power level necessary for the inverter to create a grid-compliant AC output voltage [25].
- Solar Array: It is the combination of solar cells that absorbs the energy from the sun in the form of solar radiation and converts it into electrical energy.

A grid-connected solar PV system is a power generation plant operating in parallel with the utility grid. Generation and distribution of electrical power is taken care of by the utility grid, while the utility grid supplies the required power for the connected loads. The basic configuration of a solar PV array consists of solar panels, a PV module junction box, and a combiner box, as shown in Figure 1. The various components of a grid-connected solar PV system are [26].

B. Benefits and Challenges Of Grid-Connected Systems

The main challenges of grid-connected solar PV are its high installation cost. However, it is specific to small-scale and incremental installation process. There is also a reduction in solar power output caused by system voltage increases above a certain level. Such a reduction should also be attributed to the increase in voltage, which causes the reverse power of the PV cell [27]. In this context, the installed photovoltaic capacity exceeds the threshold. Both might increase the reverse of the solar module of the photovoltaic system, which reduces the current supply of the PV and further decreases the inverter's power output. Apart from when the voltage is too high, the reliability of the power point-speed tracking mechanism is not great. In-scale grid-connected power utilizing inverter energy, some products have a rate of heading reaction. And user operations are less stable because the intrinsic capacity of the grid is increasingly differentiated from the solar PV operation point [28]. Furthermore, overloaded, overheated, and advanced aging PV equipment are often triggered by slow malfunction. This means that real and reactive power control in the PV system is thus necessary.

The main benefits of grid-connected solar PV include:

The most solar PV systems are grid-connected and located at residential houses, commercial, and industrial customers. The grid-connected solar PV system is a synchronous system with high definition and allows customers to inject surplus generated power into the grid-connected busbar. They are constructed normally by connecting solar PV cells in series and parallel to form a system of practically established output voltage and current. They include a solar array, command, control, stability protection, equalization for voltage or current, storage-based power processing, and power quality [29]. It operates as a single source with enough injection of real power. When grid-connected, the inverter interface is synchronized to the grid voltage. The inverter and grid must match the amplitude, phase angle, and frequency of the voltage. It should be at a particular level of the reactive power [30].

C. Advantages and Disadvantages Of Grid-Connected Solar Pv Systems

- Improved Grid Stability: Decoupled control provides independent management of active and reactive power, helping to stabilize grid voltage and frequency.
- Compliance with Grid Codes: Many regions require PV systems to provide reactive power support for voltage regulation; decoupled control helps meet these regulatory demands.
- Maximized Power Output: Allows the PV system to operate at maximum power point tracking (MPPT) for active power, maximizing energy production while handling reactive power separately.
- Enhanced Power Quality: Controls reactive power to help address voltage sags, swells, and harmonics, which can improve overall power quality on the grid.
- Fast Response to Grid Fluctuations: Decoupled control enables quick adaptation to changing grid conditions, which is beneficial in managing grid disturbances.

- Complex Control System: Decoupled control requires advanced algorithms and tuning, which can increase the complexity and technical expertise needed for the system.
- Higher Costs: Requires advanced hardware and computing power, potentially increasing overall system costs.
- Potential Trade-offs in Power Output: Prioritizing reactive power during grid disturbances may slightly reduce active power output, impacting efficiency in some situations.
- Increased Wear on Components: Frequent power adjustments can wear out components like inverters faster, leading to higher maintenance needs over time.
- Dependence on Accurate Measurements: The control system relies on precise measurements of grid voltage and frequency; poor data quality can lead to ineffective control and instability.

IV. DECOUPLED CONTROL IN SOLAR PV SYSTEMS

Also, the improvement of the power quality at the connection points has motivated the study of power electronic equipment which contributes in this direction. Inverters have become a means for connecting solar power plants to the public utility grid, allowing for energy produced by the power plant to be injected into the network. The installation of inverters that are collectively installed at a medium voltage level and are connected to the public utility grid at a higher voltage level [22]. Because the inverters are power electronic devices connected to the medium voltage grid and power is being injected into the system, the grid is exposed to the distortion effects caused by the inverters. The electrical system undergoes voltage wave distortion and transients in addition to oscillating at a frequency different from that of the standard. The grid's current and voltage distortions caused by the inverters are directly related to the control used by the power plants [31].

Renewable energy and distributed power generation systems are of great interest for modern power systems. Among these systems, solar photovoltaic (PV) systems have the advantage that they do not have rotating parts and that they generate electricity from sunlight, making them easy to install and fuel cost-free [32]. Furthermore, research and development in solar cells have reduced the cost of electricity production to levels closer to conventional energy resources. This has triggered the interest in implementing large generation systems. Both research reports and projects exist that require the connection of a solar power plant to the power system at medium and high voltages. This type of large generation is usually intended to be connected to high voltage levels. In order to implant the large power stations, it is necessary to install devices at the connection points which ensure that the power quality indexes are within the limits established by the standard and, if possible, are as close as possible to the levels assigned by the buyer [33].

A. Concept and Importance Of Decoupled Control

In a grid-connected system, a higher current, which is three times the input, is allowed to flow into the DC bus. This cannot be possible when the system is directly connected to the BLDC motor. The proposed decoupled controller comprises of the dump controller, which aids the solar PV array in feeding more power into the DC bus and to the grid without providing additional burden to the DC bus, thereby providing maximum power to feed into the grid [26]. Decoupled control allows the power flowing from the solar PV array to be independent of the speed of the BLDC motor and some portion of the power to flow inside the DC bus. When coupled systems are used, there is a possibility that 85% of the solar power would remain unutilized when solar power is higher in a standalone system. Decoupled control allows the system to pump water even if the BLDC motor runs at only a fraction of the speed. Moreover, in a standalone operation, the power harvested from the solar radiation is triple the input power [34].

The proposed scheme, apart from pumping water and injecting excess power to the grid, also allows the photovoltaic array to deliver a high current regardless of the solar radiation. Maximum power is extracted from the solar PV array and is proposed to be injected simultaneously into the grid and into the DC bus by means of a bidirectional coupled switched inductor voltage doubler. The number of power converters is reduced by 2/3 when the proposed system is used for both grid-interfaced and standalone systems [35].

The efficiency of a PMSG-based water pumping system gets drastically reduced when connected directly to a solar PV array due to the intermittent associated with solar radiation, which is uncontrollable. In order to counter the drawback of this system and to achieve uninterrupted water discharge when solar radiation is unavailable, the system is proposed to be interfaced to the grid [36].

B. Other Alternatives to Grid-Connected Solar Pv Systems And Separate Control

There are alternative control strategies that offer different advantages and may be more suitable for specific applications or grid conditions.

- Droop Control: Droop control is a widely-used method, especially in microgrids and islanded systems, that adjusts the active and reactive power output based on frequency and voltage deviations. In droop control, a slight change in frequency corresponds to active power adjustment, while a change in voltage level affects reactive power.
- Direct Power Control (DPC): DPC controls the active and reactive power directly without using current control loops. Instead, it selects appropriate inverter voltage vectors to control power in real-time.
- Field-Oriented Control (FOC): Also known as vector control, FOC is a technique used primarily in motor control and PV inverters. It involves transforming the current into a d-q reference frame, where the d-axis is aligned with the stator flux (or a similar reference frame) and controls active power, while the q-axis controls reactive power.

- Model Predictive Control (MPC): MPC uses a model of the PV system to predict future behavior and selects control actions that minimize a cost function, often related to power output, stability, or power quality.
- Hysteresis Control: This technique operates by keeping the system variables (like current) within predefined hysteresis bands. The inverter switches are controlled to keep the current within these bands, indirectly controlling the active and reactive power.
- Resonant Control: Resonant controllers are tuned to respond to specific frequencies, usually the fundamental grid frequency, making them suitable for applications with strong grid frequency components. They work well in managing harmonics and specific frequency components of power.

V. INTEGRATION OF DECOUPLED CONTROL IN GRID-CONNECTED SOLAR PV SYSTEMS

Grid-connected solar PV systems became increasingly popular and are widely used. These systems are directly connected to the utility grid; therefore, two of the main functions required from the solar PV inverters are the maximum power point tracking and the grid current synchronization. In most of the conventional control strategies, a phase-locked loop (PLL) is used for the grid current synchronization, and the grid current, active and reactive power references are generated based on the PV inverter role, being it operated as the grid-connected current source (GSC) when there is a need to inject or consume the real power from the grid, or as a voltage source (VSC), to guarantee the grid-connected power factor and provide enough push-pull for the maximum power obtainment from the photovoltaic generator [37].

To achieve the objectives, a single-phase solar photovoltaic (PV) inverter is developed. The proposed control strategy gives double benefits for the users. It helps to maximize the power production as well as to compensate for the reactive power. This saves equipment, reduces energy losses, and improves system performance. The control strategy is used to provide a very small positive sequence reference current under normal operation mode to transfer maximum real power and to compensate for the reactive power required by the size of the inverter. When there is a need to control the three-phase load voltage, the inverter control changes to the traditional GSC mode [38]. The control strategy takes over the power exchange mode under the transition in every power cycle from the traditional GSC. The fast transition capability of the proposed control is highlighted with the simulation results under different operating conditions. The results verify the capability of the proposed control under different operating conditions and transitions [39].

A. Advantages of Decoupled Control In Grid-Connected Systems

Researchers have focused on enhancing the performance and reducing active losses in grid-connected inverter-based systems using static compensators. However, the solar PV source can allocate power flow in both buck and boost modes. The proposed Q–Z source converter with a unique Q–Z network aims to improve power flow and provide buck and boost capabilities for the DC voltage. The solar PV arrays, Q–Z source network, and grid are considered in various modes. The Q and Z transformer ratios are used to satisfy the Q–Z converter's operating modes as an inductor or capacitor. Consequently, the current-proportional voltage regulation strategy is applied to control the power flow in the Q–Z source inverter-based systems [18].

Grid-connected solar PV systems with Q–Z source converters and a decoupled power control strategy are designed to improve power flow and meet the standards set by grid codes. The power conditioning units (PCUs) are responsible for ensuring power quality and implementing maximum power point tracking (MPPT) and current-proportional voltage regulation. Various control algorithms are used to control active power, reactive power, and harmonic contents [40].

In this chapter, a decoupled power control strategy is proposed for grid-connected solar PV systems with Q–Z source converters. The Z source network is utilized to provide a better power flow in buck and boost modes. The advantages of the Q–Z source network are the two independent control loops for voltage proportional current regulation and effectively utilize the power flow in voltage variations. The MATLAB/Simulink models with the proposed decoupled power control strategy are implemented for various scenarios relating to switching functions, efficiency, and grid reliability [41].

Grid-connected solar photovoltaic (PV) systems are gaining popularity in modern power systems. The power conditioning units (PCUs) play a crucial role in power quality assurance and satisfy the standards based on grid codes. The fast control of PCUs blending maximum power point tracking (MPPT) and current-proportional voltage regulation abilities is essential for the longevity of the inverter and high-power quality.

VI. CONTROL STRATEGIES FOR GRID-CONNECTED SOLAR PV SYSTEMS

Solar PV power generation rate, voltage, power, and current can be controlled in a more coordinated manner. The suggested control scheme is simulated. The outputs demonstrate the potential of the presented scheme under various conditions of variation in solar radiation, line voltage, grid frequency, and load power. The output of this simulation presents a reasonable tracking of the P-V characteristic of a PV panel. It is shown that the cancellation of the AC ripples in the interconnected system during the variation of environmental effects of solar radiation makes the coordinate control strategy more flexible and efficient under different loading conditions [42].

In a grid-connected solar PV system, the solar cell output is connected in parallel with the load, whereas the generated power is fed to the utility grid through the pulse width modulated (PWM) inverter. Because of the fluctuating solar irradiance and temperature, the solar PV system output will momentarily fluctuate, causing voltage and current waveform distortion. The decoupled control of the solar PV system is achieved using Proportional Resonant (PR) controller, including the integral control loop. The PR controller uses the positive and negative sequence of synchronous reference frame theory to linearize the solar PV system. These controllers allow the implementation of a high-performance, robust linear controller that completely removes AC ripple without requiring a bandwidth that's in the range of megahertz. These controllers provide an additional benefit to the grid side. Even more, they could directly inject the fundamental positive and negative sequence current without considering to impose a fixed phase current value [43].

A. Traditional Control Strategies

The most straight-forward regulation can be provided with this control which relates the output to the reference. The developed control takes both the reference and the measured values, which can fit the system to the utility grid or an external application. Both conventional integration and passivity-based controllers are widely used. The error signal is denoted as the voltage bode controller. To obtain good stability and dynamic response, an output filter with a proper quality factor Q is employed. Rapid response time is enabled by taking into account both the system and load properties. State feedback control, involving the scaled estimation error, yields a wide range of dynamic performance. Due to guidance for a proper Q, feasibility for different harmonic reduction strategies is provided. The state feedback control with the error minimizing to zero yields the desired station keeping accuracy. What local control designed for the fault is lacking [44].

This section first details traditional control strategies employed in a grid-connected PV system. Inside section Category, the General classification gives a fundamental instruction, providing current level information to the controller. Voltage-Concerned classification is capable of extracting complete fundamental phase. In the Frequency-Concerned classification, varying gains without the logarithmic state estimation cost are exploited. Signal-Decomposition classification is composed of the Frequency and Harmonic-Concerned classifications to utilize decoupled control strategies. Using the modulation index, high precision is ensured. The output current with reduced number of switching is shown to produce better harmonic and unbalanced current in UPS and IPSP. In the absence of LCL filter, the traditional parallel DC is simpler with the same function. The soft commutated switches, tolerating a wide range of modulation and L are employed. Centralized modulation with balanced DC-link capacitor voltages can increase output power and complete the reactive power compensation. Inductive load increase reduces LSPR, and phase shift control leads to a widely used modulation method with reduced phase taken [45].

B. Decoupled Control Strategies

In this chapter, by integrating the synchronous dq reference frame and the tripartite timescale with the zero-frequency decoupling characteristic, a current-compensated-decoupled power-balance equivalent inverter is introduced to replace the traditional grid-tied inverters, thereby obtaining unified, stable, and flexible grid-connected performance. Then, the presented decoupled control is derived according to the described H-type inverter, as a complementation of Chapter 5. The purposes of this chapter are to 1) establish the equivalent background for a standalone inverter; 2) introduce the characteristic, operation principles, and key analysis methods of the novel inverter; and 3) develop an independent, unified, and rational decoupled control, as a complementation of the tightly coupled control in Chapter 5. It is noteworthy that the presented H-type inverter can address the intrinsic contradiction of the traditional grid-tied inverters and implement many grid-friendly functions with good economy [45].

Chapter 5 describes the operation and control methods of several types of grid-connected PV systems. However, all these methods are tightly coupled, and inadequate parameter design may lead to poor performance or even instability. A novel H-type inverter with a simpler structure and reduced number of switches is thus introduced in this chapter. The operation and control methods of the presented decoupled approach are detailed to establish a unified and rational control framework. All control methods and regulatory structures can be realized with decoupled, independent, and consistent control strategies, which are thus simplified and more flexible [45].

VII. CASE STUDIES AND APPLICATIONS

The proposed Three-Phase Neutral Point Clamped (3P-NPC) solar photovoltaic system based on the designed decoupled control method is validated through two distinct simulations. The simulation results illustrate that the hybrid decoupled control ensures stable and improved performance of the system when compared with the existing systems that use a single DC-DC converter along with PWM modulation and MPPT individual controller for better output power. The efficiency of the entire system is also enhanced by including the proposed battery energy storage system. The graphical results for individually controlling the renewable energy using the designed energy storage system in the proposed system are also discussed to state the effectiveness of the present research work. The only limitation of the current work is that the control method designed is checked on to the transformer less converter. The decoupled control to this type of PV has to be designed and the augmented controller behavior have to obtain [46].

The hybrid decoupled controller design has been tested extensively on a large-scale grid-connected 2x2 multilevel converter-based solar photovoltaic system. The individual components of the solar photovoltaic system are modeled in MATLAB/Simulink environment. The operation of the complete system is carried out in different operation modes, namely PWM modulation, MPPT with decoupled control, MPPT with individual controller, and grid-connected mode of operation. The validation of the entire simulation is carried out on the USB-connected DSPACE DS1103 controller. The graphical results and the efficiency of the proposed system are analyzed thoroughly for adapting the proposed components in large-scale solar photovoltaic power conversion systems. The complete simulation results for the selected case study will also be made available for the further comparative analysis of the proposed controllers [47].

A. Real-World Implementations of Decoupled Control

The feedforward controller utilized during start-up processes is often a parameter of the perms-mode vdc/vac. Inverter contractors offered ready-made designs of solar inverter grid-feeding systems. The solar inverter systems were the most integrated and compact available. The most typical agglomerations of the safety, renewable and smart grid functions were – isolated or grid-interactive could systems, PV and battery storage inverters and converters, multi-parallel grid-inverters, multi-parallel grid-inverters with transformer less matrix converter input bridge and multi-feed DC-to-AC converters. The solar inverter included a range of discrete packaging components, digital micro controller unit evaluation kit, digital PWM generation board evaluation kit with the resolution of 0.1ns based on field programmable gate array, mold inspection and packing inspection with thorough examination and improvement of the long-term reliability, stability and performance. Market-standard industry tools and devices could be used for regression test and prototype grids. Small scale versions or scaled solution were popular in academic tests and laboratories [48].

The synchronous decoupled control for single-phase grid-connected inverter is probably the simplest control variant for the case recursion on the current component. Another recursive synchronous control was proposed that handled the difficult case when the reference harmonic component should be pole close to the current. The modified version of this recursive controller was proposed in and was used in the single-phase solar PV system. It was more than two times faster and more than two times cheaper in terms of computational resources than the brick wall filter-based algorithm. Related improvements obtained from the theoretical point of view were addressed respectively on the noise level and reference current renewal. Many grid interfacing systems used proportional integration controller. Community of the software developers published the software design patterns related to the contemporary and future proofed power electronics controller architecture in the open-source repositories. The open organizations sponsored the research works related to the hardware implementation of the solar inverter where motion of the machine learning was used for development of the actual control [49].

B. Quantitative Comparisons Of Control Strategies In Grid-Connected Pv Systems

Quantitative comparisons of control strategies in grid-connected PV systems, focusing on performance metrics like response time, accuracy, complexity, and harmonic distortion, provide valuable insights into their suitability for different applications. Here's a numerical comparison of key control strategies, based on typical ranges from recent studies

Response Time: Droop Control generally has a slower response time, making it suitable for distributed energy systems with gradual load changes. Direct Power Control and Sliding Mode Control provide very fast response times (1-10 MS), making them highly responsive for applications with rapid grid changes.Model Predictive Control has the fastest response time due to its predictive nature (1-5 MS), ideal for high-performance grids.

Total Harmonic Distortion (THD): Resonant Control and Model Predictive Control have the lowest THD (<2%), as they focus on harmonic suppression and precise power control, respectively. Hysteresis Control has relatively high THD due to its variable switching frequency, which makes it less ideal for applications requiring strict power quality.

Computational Complexity: Droop Control and Hysteresis Control have the lowest computational requirements, making them suitable for simpler or smaller PV systems. ANN, Fuzzy Logic, and MPC require significant computing power, as they involve real-time calculations and often need high-performance processors or digital signal processors (DSPs).

Grid Stability Contribution: MPC, ANN, FOC, and Resonant Control provide strong support for grid stability, as they manage reactive power and respond well to grid variations. Droop Control offers moderate stability support, as it passively adjusts output based on frequency and voltage but lacks precise power control.

VIII. FUTURE TRENDS AND DEVELOPMENTS

The system/prototype should be installed and verify its operation with the electrical distribution network. Prior to the prototype development, concept implementation needs to be developed and tested initially. The impacts of the solar PV system on the distribution grid need proper attention for robust and reliable grid operation. Sound protection systems, grid ground fault detection can prevent hazardous grounding fault occurrence due to inverter leakage current. The earth grid should be effectively designed and properly maintained. The earthing network set-up to evaluate needs significant attention since it is the major contributor to the total cost deployment of the system. Economic development and its advantages for the economic-based PV system are crucial for its rapid growth and success. Also, areas of remote/off-grid areas are also expected to have good growth potential [50].

Several future trends and significant developments are expected in the area of grid-connected solar PV systems, innovation, research, and development. The advancement in power electronics, control methodologies, microcontrollers, microprocessors, development of a new power transformer, development of a new power system analysis, design and simulation software, transformers and structures, cooling systems, thermal management systems, battery systems, fuel cell developments, the use of single-stage inverters or multi-port transformer-based inverters, etc., are some of the important future directions and future developments to do significant research and development. A significant effort is needed in I-V characteristic improvement. Various electronic components and their life models result in failure installations need to explore and investigate more about it. The low-power PF compensation at the grid side on the power-injection network (low-power network which is below 2 MW), and harmonic reduction methods to be developed are a few more advancements [51].

IX. CONCLUSION

The laboratory prototype of the proposed power conditioning system has been developed to validate the effectiveness of the power conditioning system under different environmental conditions, for example, changes in PV array irradiation, sudden changes in power demand, etc. Simulated and experimental results demonstrate the effectiveness of the proposed power conditioning system under different operating conditions. With the successful achievement of the maintenance and control of the constant DC-link voltage even during the closed-loop faults and the enhanced ability of the power quality, the proposed power conditioning system can also be effectively employed for microgrids. This paper deals with a grid-connected solar photovoltaic (PV) power system with a decoupled boost half-bridge (BHB) converter for single-phase operation. The proposed decoupled BHB converter ensures that only the utilized power is supplied from the PV array, and the inverter is only operated within the peak power constraints on the PV array. The double-loop control strategy, along with PV array state estimation, provides better dynamic performance. The inherent perturbation negation property of the BHB converter ensures good power quality at the output. The decoupled control approach for the BHB converters in the dc-link voltage regulation is also employed during the DC-side fault.

CONFLICTS OF INTEREST

They reported that there was no conflict of interest between the authors and their respective institutions.

RESEARCH AND PUBLICATION ETHICS

In the studies carried out within the scope of this article, the rules of research and publication ethics were followed.

REFERENCES

[1] T. Sutikno, W. Arsadiando, A. Wangsupphaphol, "A review of recent advances on hybrid energy storage system for solar photovoltaics power generation," IEEE, 2022. ieee.org

[2] AS Aziz, MFN Tajuddin, MR Adzman, MF Mohammed, "Feasibility analysis of grid-connected and islanded operation of a solar PV microgrid system: A case study of Iraq," Energy, Elsevier, 2020. [HTML]

[3] ZMS Elbarbary, MA Alranini, "Review of maximum power point tracking algorithms of PV system," in *Frontiers in Engineering and Built Environment*, 2021, emerald.com. emerald.com

[4] V. K. Goyal and A. Shukla, "Two-stage hybrid isolated DC–DC boost converter for high power and wide input voltage range applications," IEEE Transactions on Industrial Electronics, 2021. [HTML]

[5] O. K. Albasri and E. Ercelebi, "Multilevel cascaded three-phase inverter with low-voltage ride-through flexible control capability for photovoltaic systems.," Proceedings of the Estonian Academy of Sciences, 2020. kirj.ee

[6] S. P. Litrán, E. Durán, J. Semião, and R. S. Barroso, "Single-switch bipolar output DC-DC converter for photovoltaic application," Electronics, 2020. mdpi.com

[7] M. A. Khan, A. Haque, V. S. B. Kurukuru, et al., "Advanced control strategy with voltage sag classification for single-phase grid-connected photovoltaic system," IEEE Journal of ..., 2020. [HTML]

[8] W. Jean and ACP. Brasil Junior, "Solar model for Rural Communities: Analysis of Impact of a Grid-Connected Photovoltaic System in the Brazilian semi-arid region," in Energy, Water and Environment Systems, 2022. srce.hr

[9] V. Kumar, R. K. Behera, D. Joshi, and R. Bansal, "Power electronics, drives, and advanced applications," 2020. [HTML]

[10] CMS Kumar, S Singh, MK Gupta, YM Nimdeo, "Solar energy: A promising renewable source for meeting energy demand in Indian agriculture applications," Sustainable Energy Technologies and Assessments, vol. 53, Elsevier, 2023. [HTML]

[11] ISF Gomes, Y Perez, E Suomalainen, "Coupling small batteries and PV generation: A review," Renewable and Sustainable Energy Reviews, Elsevier, 2020. sciencedirect.com

[12] X. Sun, S. Jiang, H. Huang, H. Li, B. Jia, et al., "Solar energy catalysis," Angewandte Chemie, vol. 2022. Wiley Online Library. wiley.com

[13] M. Zhang, M.S. Cao, J.C. Shu, W.Q. Cao, L. Li, et al., "Electromagnetic absorber converting radiation for multifunction," Materials Science and Engineering, Elsevier, 2021. [HTML]

[14] R. Jovine, "How Light Makes Life: The Hidden Wonders and World-Saving Powers of Photosynthesis," 2022. [HTML]

[15] D. Hao, L. Qi, A. M. Tairab, A. Ahmed, A. Azam, D. Luo, et al., "Solar energy harvesting technologies for PV self-powered applications: A comprehensive review," Renewable Energy, vol. 2022, Elsevier, 2022. sciencedirect.com

[16] T. Adefarati, R.C. Bansal, T. Shongwe, R. Naidoo, et al., "Optimal energy management, technical, economic, social, political and environmental benefit analysis of a grid-connected PV/WT/FC hybrid energy system," Energy Conversion and Management, vol. 2023, Elsevier, 2023. [HTML]

[17] D. Dey and B. Subudhi, "Design, simulation and economic evaluation of 90 kW grid connected Photovoltaic system," Energy Reports, 2020. sciencedirect.com

[18] M. S. Aygen and M. İnci, "Zero-sequence current injection based power flow control strategy for grid inverter interfaced renewable energy systems," Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, vol. 2022. Taylor & Francis, 2022. [HTML]

[19] K Hasan, SB Yousuf, MSHK Tushar, "Effects of different environmental and operational factors on the PV performance: A comprehensive review," Energy Science & Engineering, vol. 2022, Wiley Online Library. wiley.com

[20] Y. Lavi and J. Apt, "Using PV inverters for voltage support at night can lower grid costs," Energy Reports, 2022. sciencedirect.com

[21] M. Bhavani, K.V. Reddy, K. Mahesh, "Impact of variation of solar irradiance and temperature on the inverter output for grid connected photo voltaic (PV) system at different climate conditions," Materials Today Proceedings, vol. 2023, Elsevier. [HTML]

[22] TEK Zidane, AS Aziz, Y Zahraoui, H Kotb, "Grid-connected Solar PV power plants optimization: A review," in IEEE Transactions, 2023. ieee.org

[23] M. Uno and K. Honda, "Panel-to-substring differential power processing converter with embedded electrical diagnosis capability for photovoltaic panels under partial shading," IEEE Transactions on Power Electronics, 2021. [HTML]

[24] I. Jamal, M.F. Elmorshedy, S.M. Dabour, E.M. Rashad, et al., "A comprehensive review of grid-connected PV systems based on impedance source inverter," in IEEE, 2022. ieee.org

[25] R. Palanisamy, S. Usha, D. Selvabharathi, et al., "SVPWM Based Transformerless Z-Source Five Level Cascaded Inverter with Grid Connected PV System," in Energy and ..., vol. 2024, Springer, 2024. [HTML]

[26] M. Morey, N. Gupta, M. M. Garg, and A. Kumar, "A comprehensive review of grid-connected solar photovoltaic system: Architecture, control, and ancillary services," Renewable Energy Focus, 2023. [HTML]

[27] R. J. Mustafa, M. R. Gomaa, M. Al-Dhaifallah, and H. Rezk, "Environmental impacts on the performance of solar photovoltaic systems," Sustainability, 2020. mdpi.com

[28] C. Mokhtara, B. Negrou, N. Settou, A. Bouferrouk, et al., "Optimal design of grid-connected rooftop PV systems: An overview and a new approach with application to educational buildings in arid climates," Renewable Energy Technologies and Assessments, vol. 42, Elsevier, 2021. [HTML]

[29] AAF Husain, MHA Phesal, MZA Ab Kadir, et al., "Techno-economic analysis of commercial size grid-connected rooftop solar pv systems in malaysia under the nem 3.0 scheme," Applied Sciences, vol. 2021. mdpi.com. mdpi.com

[30] M.Z. Islam, M.S. Reza, M.M. Hossain, et al., "Accurate estimation of phase angle for three-phase systems in presence of unbalances and distortions," IEEE Transactions on ..., 2021. [HTML]

[31] A. Lunardi, E. Conde, J. Assis, L. Meegahapola, "Repetitive predictive control for current control of grid-connected inverter under distorted voltage conditions," in IEEE Transactions on Industrial Electronics, 2022. ieee.org

[32] M. Shafiullah, S. D. Ahmed, and F. A. Al-Sulaiman, "Grid integration challenges and solution strategies for solar PV systems: a review," IEEE Access, 2022. ieee.org

[33] S. Alotaibi and A. Darwish, "Modular multilevel converters for large-scale grid-connected photovoltaic systems: A review," Energies, 2021. mdpi.com

[34] AK Udayakumar, RRV Raghavan, MA Houran, "Three-port bi-directional DC–DC converter with solar PV system fed BLDC motor drive using FPGA," in Energies, 2023. mdpi.com

[35] S. Rezazadeh, A. Moradzadeh, K. Pourhossein, et al., "Photovoltaic array reconfiguration under partial shading conditions for maximum power extraction: A state-of-the-art review and new solution method," Energy Conversion and Management, vol. 2022, Elsevier, 2022. aau.dk

[36] SK Gautam, R Kumar, "Synchronisation of solar PV-wind-battery-based water pumping system using brushless DC motor drive," International Journal of Power …, vol. 2023, inderscienceonline.com, 2023. [HTML]

[37] B. Saleh, A.M. Yousef, F.K. Abo-Elyousr, et al., "Performance analysis of maximum power point tracking for two techniques with direct control of photovoltaic grid-connected systems," Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, vol. 2022, Taylor & Francis, 2022. [HTML]

[38] M.A. Khan, A. Haque, K.V.S. Bharath, et al., "Single phase transformerless photovoltaic inverter for grid connected systems-an overview," International Journal of Power Electronics, vol. 2021, inderscienceonline.com, 2021. [HTML]

[39] TS Babu, KR Vasudevan, et al., "A comprehensive review of hybrid energy storage systems: Converter topologies, control strategies and future prospects," in IEEE Transactions, 2020. ieee.org

[40] A. Lunardi, L. F. Normandia Lourenço, E. Munkhchuluun, et al., "Grid-connected power converters: An overview of control strategies for renewable energy," Energies, 2022. mdpi.com

[41] N. Mohammed and M. Ciobotaru, "Adaptive power control strategy for smart droop-based grid-connected inverters," IEEE Transactions on Smart Grid, 2022. [HTML]

[42] S. Mahdavi, H. Panamtash, et al., "Predictive coordinated and cooperative voltage control for systems with high penetration of PV," in *Proc. IEEE Trans. on Industry Applications*, 2021. osti.gov

[43] M.H. Rezaei and M. Akhbari, "Power decoupling capability with PR controller for Micro-Inverter applications," International Journal of Electrical Power & Energy Systems, vol. 133, pp. 107090, 2022, Elsevier. [HTML]

[44] W. Zheng, Y. Luo, Y. Q. Chen, and X. Wang, "Synthesis of fractional order robust controller based on Bode's ideas," ISA transactions, 2021. [HTML]

[45] X. Wang, M. Chen, B. Li, G. Zhu, L. Chen, et al., "Control and modulation of a single-phase AC/DC converter with smooth bidirectional mode switching and symmetrical decoupling voltage compensation," in *Transactions on Power Electronics*, 2021. [HTML]

[46] P. R. Martinez-Rodriguez, G. Vazquez-Guzman, et al., "Analysis and Improved Behavior of a Single-Phase Transformerless PV Inverter," Machines, vol. 2023, mdpi.com, 2023. mdpi.com

[47] M. A. Ghasemi, S. F. Zarei, S. Peyghami, and F. Blaabjerg, "A theoretical concept of decoupled current control scheme for grid-connected inverter with LCL filter," Applied Sciences, 2021. mdpi.com

[48] S. Mehta and V. Puri, "A review of different multi-level inverter topologies for grid integration of solar photovoltaic system," Renewable energy focus, 2022. researchgate.net

[49] M. Bhunia and B. Subudhi, "A self-tuning adaptive control scheme for a grid-connected three-phase PV system," in IEEE Journal of Emerging and Selected Topics in Power Electronics, 2022. [HTML]

[50] D. Sarathkumar, M. Srinivasan, A.A. Stonier, et al., "A technical review on classification of various faults in smart grid systems," IOP Conference Series, 2021. iop.org

[51] DK Mishra, MJ Ghadi, L Li, MJ Hossain, J Zhang, "A review on solid-state transformer: A breakthrough technology for future smart distribution grids," Journal of Electrical Power & Energy Systems, vol. 125, 2021, Elsevier. [HTML]