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A Review of Fault Ride through Approach in Solar Photo Voltaic System

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ABSTRACT

In order to maintain system stability during grid disturbances, effective Fault Ride Through (FRT) solutions are now required due to the integration of solar Photovoltaic (PV) systems into power grids. This review examines the significance and difficulties of various FRT strategies used in solar PV systems. Voltage support, current control, active power control and sophisticated control algorithms are among the ways that are examined. Grid code compliance issues, equipment costs, control complexity issues and transient response issues are mentioned as challenges. The integration of AI and machine learning, grid code standardisation and the creation of hybrid FRT solutions are a few more potential future possibilities that are noted. Refining FRT methods in solar PV systems has promise for improved grid resilience and consistent energy delivery as the renewable energy landscape changes.

Keywords: Solar photovoltaic systems; Fault ride through; FRT approaches; Grid integration; Voltage support; Current control; Active power control; Advanced control algorithms; Grid code compliance; Equipment cost; Control complexity; Transient response; AI and machine learning; Standardization; Hybrid FRT solutions; Renewable energy; Grid stability

INTRODUCTION

Due to the fact that solar Photovoltaic (PV) systems have been successfully integrated into contemporary power grids, there is a present growth in the demand for Fault Ride Through (FRT) solutions that are reliable and robust. Photovoltaic (PV) systems are able to endure disruptions in the grid and recover after they have taken place as a result of these ways. They do this to ensure the reliability and efficiency of the renewable source of energy, in addition to the grid as a whole, which is the result of their actions. This section gives a full overview of the context, reasons and objectives of the review. Additionally, it addresses the topic of why the review was carried out in the first place [1].

Background

Solar photovoltaic systems are becoming an increasingly popular option that may be utilized in this transition as the world progresses towards the utilization of energy sources that are less destructive to the environment and more sustainable. The expanding use of solar Photovoltaic (PV) systems on a wide range of scales, spanning from home to utility-level installations, has led in the creation of new difficulties around the preservation of grid stability. These new challenges include. These difficulties are a direct result of

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the rising use of Photovoltaic (PV) systems in the world's energy networks. Not only can grid faults, which can include voltage dips, short circuits and other types of disruptions, have a negative influence on the solar PV system itself, but they can also have a severe impact on the grid infrastructure that is immediately surrounding it. Grid faults can have a negative influence on the solar PV system itself. Grid faults can have a negative influence on the grid infrastructure that is directly surrounding it. One of the most important aspects of integrating the grid is making certain that even in the event that there are issues, these systems will continue to operate normally.

Motivation

Researchers were inspired to investigate FRT methodologies for use in solar Photovoltaic (PV) systems as a source of motivation by the necessity of establishing a resilient and reliable energy landscape. This necessity prompted the researchers to conduct their research. Because of this necessity, the researchers began looking into the various ways [2]. When it comes to the integration of solar photovoltaic systems, the main considerations should be giving top priority to providing a steady supply of electricity, protecting the stability of the electrical grid and making the most of opportunities to use renewable forms of energy. Stakeholders in the renewable energy sector, such as researchers, engineers, policy-makers and industry experts, can work together to address difficulties and contribute to the development of sustainable energy solutions if they first analyses and get a knowledge of the many FRT approaches. This can be accomplished by analyzing and obtaining an understanding of the various FRT approaches.

Objectives

The following is a list of the key objectives of this investigation. This objective has been established with the intention of achieving an in-depth investigation of the numerous FRT methods that are utilized in solar PV systems, with a particular emphasis on the mechanisms of these methods and the benefits that they give. Determine the challenges and considerations that must be made while using FRT approaches, such as compliance with grid codes, the cost of equipment, control complexity and transient response. This seminar will discuss potential future paths in FRT research and application, such as the incorporation of artificial intelligence and machine learning, initiatives to standardize FRT systems and the creation of hybrid FRT solutions. This project aims to make a contribution to the overall understanding of FRT approaches and the role they play in increasing the dependability and stability of solar PV systems within the context of power grids more broadly. This will be accomplished by making a contribution to an existing body of knowledge. By meeting these objectives, the purpose of this review is to encourage innovation and informed decision-making in the renewable energy sector. Additionally, this review's objective is to provide substantial insights into the FRT landscape for solar PV systems [3].

LITERATURE REVIEW

The incorporation of solar Photovoltaic (PV) systems into power grids has resulted in the requirement for efficient Fault Ride Through (FRT) techniques, which ensure the PV systems and the grid continue to function normally and remain stable. Over the course of the past few years, academics and engineers have investigated a variety of FRT strategies in order to overcome the issues given by grid disruptions. This literature review examines the existing body of information concerning FRT techniques in solar PV systems, high-lighting major results, advancements and topics for further research. The assessment of the existing body of knowledge is called a literature review.

Strategies for providing voltage support providing voltage support is a basic component of FRT methods. The provision of instantaneous voltage support by Energy Storage Systems (ESS) is an important function that plays an important role in the event of grid disruptions. ESS, which can include batteries and supercapacitors, can either inject or absorb reactive power to manage voltage levels. This allows Photovoltaic (PV) systems to function normally even when the voltage drops. Numerous research have been conducted to study the most effective methods of voltage support, including optimal sizing, control tactics and integration of ESS. In addition, reactive power compensation strategies, which include making adjustments to the settings of the inverter, have been investigated as a potential means of improving the FRT capabilities of PV systems. These strategies place an emphasis on the significance of preserving stable voltage profiles during fault events in order to prevent grid disconnection and to ensure that the grid is resilient.

Techniques for controlling the current current-based FRT approaches center on the management of the current that is injected into the grid by the PV system when there is a fault. In order to reduce the amount of current that the PV inverters contribute to fault currents, current reference adjustment solutions entail dynamically adjusting the current setpoints of the inverters. It has been discovered that using this method can reduce the fault-induced strains placed on the PV system as well as the grid. In addition, current limiting measures have been proposed as a means of lowering fault currents. These tactics include the utilization of active power curtailment and reactive power injection. These methods emphasize the significance of controlled current injection in preserving the stability of the grid and reducing the risk of potential harm [4].

Methods of active power control active power control strategies entail reducing the amount of electricity that is output by the PV system whenever there is a fault occurrence. PV systems can prevent the grid from becoming overloaded and promote a smoother ride through faults by decreasing the amount of active electricity generation they produce. Power reduction strategies have the dual objectives of preserving the reliability of the grid while also maximizing the amount of energy that may be generated. To improve the overall system's stability, grid load management strategies have been developed. These strategies entail modifying the amount of power consumed by particular loads during fault events.

Advanced control algorithms: Recent study has demonstrated a growing interest in the implementation of advanced control algorithms to increase FRT capabilities. This interest has been shown to be on the rise. One such method, known as Model Predictive Control (MPC), is designed to predict grid disturbances and make proactive adjustments to the control parameters of Photovoltaic (PV) systems. The outcomes that MPC has shown so far are quite encouraging in terms of improving fault ride through performance and grid stability. PV systems are able to respond swiftly to faults and disturbances because to adaptive control algorithms, which dynamically adjust to the changing conditions of the grid. The incorporation of real-time optimization strategies is shown to further improve the capacity of PV systems to work through failure situations.

The use of FRT techniques is plagued by a number of persistent difficulties, as well as potential future courses of action. Grid code compliance is still an extremely important factor to think about, especially given that many countries have varying FRT standards. Economic constraints arise from the necessity of striking a balance between the benefits of greater FRT capability and the additional costs of equipment, such as energy storage systems. It is also necessary to address the issue of control complexity in order to guarantee the dependability and efficiency of FRT techniques. In addition, the features of the transient response play a crucial part in deciding whether or not FRT techniques are successful in the presence of dynamic fault situations.

In looking to the future, it is recommended that future research concentrate on combining artificial intelligence and machine learning approaches in order to forecast and respond to fault situations in real time. Standardization initiatives are essential if uniform FRT requirements are to be established worldwide in order to streamline the integration of solar Photovoltaic (PV) systems. It is possible to provide comprehensive fault ride through performance in a variety of grid settings with the help of hybrid FRT systems, which combine several methodologies [5].

The research that was looked into underlines the significance of FRT techniques in solar PV systems for the purpose of ensuring grid stability and providing a steady supply of energy. The improved FRT capabilities of PV systems is the result of the combined efforts of a number of factors, including voltage support, current control, active power regulation and better control algorithms. Ongoing research and technological improvements have the ability to further refine FRT tactics, despite the difficulties associated with grid code compliance, the expense of equipment and the complexity of control systems. FRT strategies will become increasingly important in the establishment of a resilient and sustainable energy future as the landscape of renewable energy continues to undergo change.

DISCUSSION

Fault Ride Through (FRT) Approaches

FRT strategies are essential for maintaining the stability of solar Photovoltaic (PV) systems during grid faults. This section explores various FRT approaches that enable PV systems to ride through fault events seamlessly (**Figure 1**).

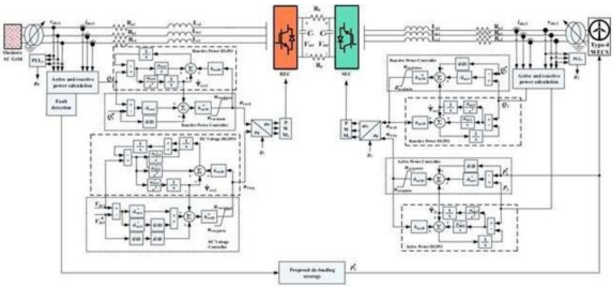

Figure 1: VSC-HVDC systems with type-4 Wind Energy Conversion Systems (WECS).

Voltage Support Strategies

The goal of voltage support techniques is to keep voltage levels consistent at the point of connection; this makes it possible for PV systems to continue operating even when there are failures in the grid.

Energy storage systems: Voltage support is significantly aided by Energy Storage Systems (ESS), which play an essential part. ESS is able to either inject or absorb reactive power in the event of a fault in order to maintain the grid's voltage. Batteries, supercapacitors and flywheels are examples of popular types of devices that are used to store energy. PV systems that are equipped with ESS are able to react quickly to drops in voltage, which helps to maintain a continuous supply of electricity and avoids disconnections.

Reactive power compensation: Adjusting the reactive power output of PV inverters is required in order to perform reactive power compensation. PV systems have the ability to adjust grid voltage since they can either inject or absorb reactive power. This method necessitates the use of precise control algorithms so that a rapid response may be given to fault conditions. PV systems that utilize reactive power compensation are better able to withstand the voltage swings that are brought on by grid outages [6].

Current Control Techniques

During a fault occurrence, the primary emphasis of current control strategies is on the management of the current injected into the grid by Photovoltaic (PV) systems.

Current reference adjustment: During fault situations, this method will dynamically alter the current setpoints of any PV inverters that are connected to the system. PV systems reduce the amount of strain placed on the grid by lowering the amount of current that may be contributed to fault currents. This method both increases the chance of the grid being stable and decreases the possibility of any harm being done to the PV system.

Current limiting strategies: Controlling the power output of photovoltaic systems is one of the current-limiting approaches that may be used to reduce fault currents [13]. Active power curtailment is the process of reducing the amount of active power production that occurs during disturbances in order to minimize system overload. Injecting reactive power may efficiently restrict fault currents, which is another advantage. These solutions highlight the importance of regulated current injection in the process of preserving the integrity of the grid (**Table 1**).

Table 1: System parameters.

AC grid frequency	f	50 Hz
AC grid base voltage	VAC_{base}	100 kV
DC link base voltage	VDC_{base}	200 kV
AC grid base power	S_{base}	100 MVA
AC grid line resistance (25 km)	R_1, R_2	0.05 Ω/km
AC grid line inductance (25 km)	L_1, L_2	0.026 mH/km
DC link resistance (50 km)	R_0	0.21 Ω/km
DC bus capacitance	C_1, C_2	11.94 µF

Active Power Control Methods

In order to improve FRT capabilities, active power control approaches focus their attention on finding ways to reduce the power output of PV systems.

Power curtailment: During times when there is a problem, power curtailment includes temporarily limiting the amount of electricity that is actively generated by PV systems. This strategy helps to contribute to a smoother ride through faults and greater grid stability by minimizing the injection of excessive amounts of electricity. In order to preserve a healthy equilibrium between grid support and energy production careful optimization of power curtailment levels is very necessary.

Grid load management: During fault circumstances, the objective of grid load management methods is to move or shed loads. PV systems are able to regulate power imbalances and stabilize the grid because of their ability to alter the consumption of certain loads. In order to guarantee efficient fault ride through with no negative impact on the user experience, this method necessitates the use of sophisticated load management algorithms [7].

Advanced Control Algorithms

The use of advanced FRT techniques may improve the responsiveness and efficiency of PV systems while they are experiencing fault occurrences. Advanced control algorithms provide these tactics (**Table 2**).

Table 2: Integral of Absolute Error (IAE) indices (in p.u.) of different control schemes calculated in different cases.

Simulation cases	Variables	Control approaches	
		Deloading VC	**Delaoding NAC**
35% Voltage sag nominal model	IAE_{iq1}	0.131	0.1223
	IAE_{P1}	0.613	0.6041
	IAE_{VDC}	0.561	0.5432
30% AC system parameter mismatches	IAE_{iq1}	0.212	0.1323
	IAE_{iq2}	0.3964	0.2011
	IAE_{VDC}	0.7546	0.5439
30% DC system parameter mismatches	IAE_{iq1}	0.2713	0.143
	IAE_{iq2}	0.5063	0.2103
	IAE_{VDC}	0.9043	0.6034

Model Predictive Control (MPC): Adaptive control strategies dynamically adjust system parameters based on real-time feed-back from grid conditions. This approach ensures adaptability to changing fault scenarios, optimizing FRT performance. Adaptive control techniques contribute to robust fault ride through capabilities in varying grid environments.

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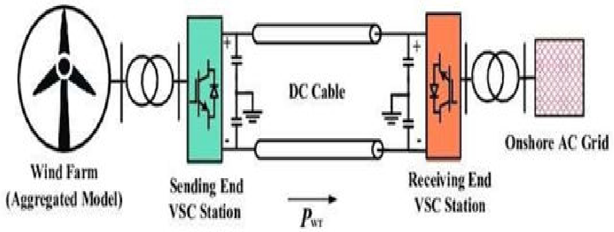

Figure 2: The configuration of the voltage-source converter-based high voltage direct current (VSC-HVDC) system.

Real-time optimization: Real-time optimization approaches continually optimize system responses during fault events. By iteratively adjusting control inputs based on real-time data, PV systems can effectively navigate through transient fault conditions. Real-time optimization enhances the reliability and efficiency of fault ride through strategies. In a comprehensive range of FRT approaches exists to enhance the resilience of solar PV systems during grid faults. Voltage support, current control, active power management and advanced control algorithms collectively contribute to successful fault ride through, ensuring continuous operation and grid stability. The choice of approach depends on system requirements, grid codes and the desired balance between stability and energy generation [8].

Challenges and Considerations

Fault Ride Through (FRT) solutions need to be properly incorporated into solar Photovoltaic (PV) systems in order to ensure grid stability and a steady supply of renewable energy. This is highly important. Nevertheless, there are a number of challenges and aspects that need to be carefully considered in order to enhance the effectiveness of these methods and guarantee that they are practicable (**Figure 3**) [9].

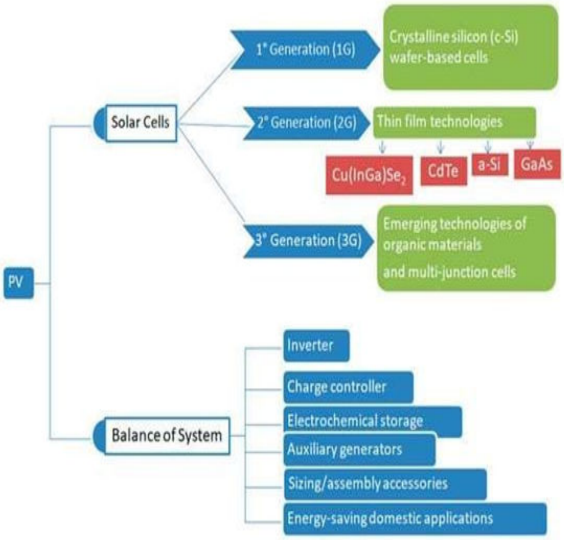

Figure 3: Photovoltaic (PV) system overview.

Grid Code Compliance Challenges

Grid codes are essentially legislative frameworks that establish the exact technical criteria and standards that must be adhered to in order for renewable energy facilities to be linked to the grid. In other words, grid codes are necessary for connecting renewable energy facilities to the grid. Certain requirements and expectations must be satisfied before renewable power facilities may be connected to the electrical grid. In spite of the fact that these protocols are responsible for maintaining the reliability and safety of the grid, the implementation of FRT techniques is made more complex as a direct result of these protocols. Because so many nations and regions have their very own unique grid codes, the FRT criteria that each one of them has in place tends to be rather different from those of the other countries and areas. Because there are so many different criteria, it may be difficult for PV system developers to construct FRT systems that are versatile enough to fulfil a wide variety of needs. This is because there are so many different requirements [10].

There is a possibility that generating FRT plans that are compliant with a number of various grid regulations will be a process that is not only challenging but also time consuming. To effectively negotiate a complicated set of technical criteria, manufacturers and system integrators are required. Some of these needs include tolerances for voltage and frequency, fault-clearing intervals and support for reactive power. Other requirements include support for reactive power. Support for a predetermined quantity of electricity is one example of another kind of technical criterion. The process of adapting FRT techniques to suit the needs of a varied grid code may result in an increase in control complexity and may potentially restrict the system's performance. Adapting FRT approaches to meet the requirements of a varied grid code. It is possible that this is the case as a result of the possibility for increasing control complexity [11].

Equipment Cost Implications

When FRT technologies are incorporated, it is often essential to acquire extra hardware, such as Energy Storage Systems (ESS) or specialised control systems. This may be the case in certain instances. It's possible that this may be a time-consuming and expensive procedure. Despite the fact that these technologies make Photovoltaic (PV) systems more durable in the face of fault occurrences, it is probable that the implementation of these technologies will have a substantial effect on the costs associated with the projects. To be more specific, it is probable that the ESS will account for a significant portion of the total expenditures incurred by the system.

Finding a happy medium between the financial advantages that come with expanded FRT capacity and the expenses that are con-nected with the purchase, installation and care of the equipment is a challenge. However, it is necessary in order to create a solution that will work for all parties involved. There is a chance that this task may be difficult to complete. The extent to which a project may be economically viable is becoming an increasingly important factor to think about. This is especially true for solar power installations that are on a smaller size or for businesses that face considerable financial constraints. There is a chance that the cost of the FRT-enhancing technology may dissuade some stakeholders, while others may believe that the long-term advantages of less downtime, improved energy output and better grid stability make the investment worthwhile [12].

Control Complexity Issues

When using more complicated FRT techniques, it is sometimes necessary to make use of extensive control algorithms and to co-ordinate a wide number of diverse system components. This may be a challenging undertaking. Because of the complexity of these control schemes, there is a chance that their stability, robustness and compatibility with other control systems may be compromised. This is a possibility because of the complexity of these control schemes. When integrating new control algorithms with older systems or adapting these algorithms to a number of various configurations of Photovoltaic (PV) systems, one has to have experience as well as undertake thorough testing in order to ensure that the algorithms work as intended.

In addition to this, the complicated nature of the control raises questions about the dependability of the system in addition to its upkeep. When working with complex control algorithms, there is a larger chance that mistakes, failures and unanticipated interactions may take place. One of the most pressing challenges in this sector is the difficulty of guaranteeing that Photovoltaic (PV) systems can maintain their stability in the face of a diverse selection of fault scenarios. This issue has arisen as one of the most pressing worries in this sector. In addition, the individuals who are in charge of running the system and maintaining it need particular training in order to be able to correctly comprehend and work with the complex control methods. This is necessary in order to ensure that the system continues to function as intended [13].

Transient Response Concerns

When it comes to FRT methodologies, the idea of transient response, which explains how quickly a system reacts to unexpected changes in input or conditions, is of the highest relevance. This is because transient response indicates how quickly a system responds to unexpected changes. In the event that the grid experiences disruptions, Photovoltaic (PV) systems need to respond in a timely and accurate manner in order to maintain grid stability and prevent disconnection. Grid instability may be made worse by delayed or inappropriate reactions, which may then lead to variations in voltage or even power outages. Grid instability may also be caused by a combination of factors.

It is necessary to do exhaustive parameter tuning, comprehensive dynamic modelling and testing that is based on simulation in order to build FRT algorithms that have an optimal response to transients. Finding a happy medium between having fast response times and avoiding overshoots and oscillations in the system is a challenging and nuanced endeavor that requires careful attention to detail. The design process is made much more difficult by the fact that the characteristics of the transient response may change in accordance with the specific FRT approach that is used, which further complicates matters [14].

The complexity of the process of grid integration for solar photo-voltaic projects may be shown by the challenges and considerations that must be made when FRT methods are used. Collaboration between academics, engineers, lawmakers and industry participants is going to be essential if we are going to be successful in overcoming these challenges. The development of standardized FRT solutions that find a happy medium between grid code compliance, equipment prices, control complexity and concerns over transient response is required in order to extract the full potential of solar Photovoltaic (PV) systems as reliable contributors to the modern energy environment. These solutions must be implemented in order to realize the full potential of solar Photovoltaic (PV) systems.

Future Directions

The development of Fault Ride Through (FRT) technologies in solar Photovoltaic (PV) systems offers tremendous potential and is progressing at a rapid rate in today's ever-changing renewable energy market. Enhancing fault resilience, grid stability and the seamless integration of solar photovoltaic systems into contemporary power grids are the primary focuses of future research and implementation initiatives for FRT (**Figure 4**).

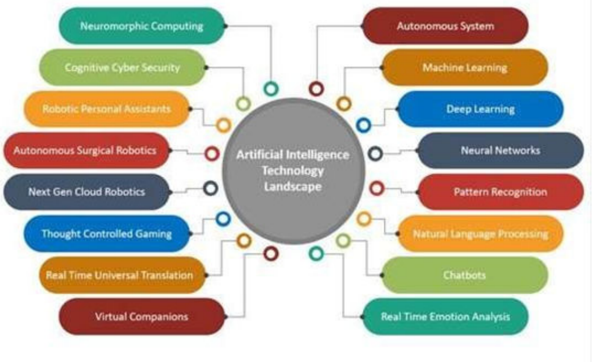

Figure 4: AI technology landscape.

Integration of AI and Machine Learning

The incorporation of Artificial Intelligence (AI) and Machine Learning (ML) tactics is a step forward on the route towards the development of FRT strategies. The use of AI and ML allows for the prediction of grid disruptions, the quick analysis and optimization of complicated fault situations and the real-time optimization of control actions. AI-driven FRT techniques may proactively adjust to dynamic grid circumstances by learning from previous data on faults and the behavior of the system. This results in improved fault detection as well as overall system performance. This integration has the potential to completely change the FRT industry by allowing intelligent PV systems that are capable of autonomous fault management and learning on their own [15].

Standardization of Grid Codes

Standardization initiatives are of the utmost importance if one want to encourage the wider use of FRT techniques. The incorporation of solar Photovoltaic (PV) systems into various power networks may be facilitated by collaborative activities aiming at harmonizing grid codes in a number of different locations. The design and execution of FRT strategies will be simplified as a result of the establishment of universal rules for the needs of FRT, which will also reduce complexity and ensure consistent performance. Standardization not only makes international cooperation easier, but it also speeds up the implementation of solutions that use renewable energy sources.

Hybrid FRT Solutions

A complete solution for addressing a wide variety of grid problems may be found in hybrid FRT systems, which incorporate different methodologies. When approaches for voltage support, current control and active power management are integrated, it is possible to build fault resilience that is resilient over a broad spectrum of fault kinds and degrees of failure severity. These hybrid strategies have the potential to give flexibility in adjusting to different grid situations while still preserving grid stability. On the other hand, the difficulty is in optimizing the coordination and interaction between the various FRT components in order to accomplish fault ride through without interruption.

Innovative Control Techniques

The development of new control methods is still the primary factor driving FRT developments. New control algorithms that can dynamically modify system parameters based on real-time data and prediction models are now the focus of a lot of research at universities across the world. The precision of the fault response, the transient stability and the overall system dependability may all be improved using enhanced control procedures. In addition, the incorporation of control techniques from other sectors, like as robots and aerospace, might provide new viewpoints and innovative solutions to problems that are present in the FRT sector [16].

The introduction of FRT techniques into solar photovoltaic systems in the near future carries with it the possibility of significantly altering the existing landscape of renewable energy sources. The reliability and resiliency of PV systems may be significantly improved during grid disturbances *via* the use of AI and machine learning, the standardization of grid codes, the development of hybrid solutions and the adoption of new control approaches. Not only do these prospective courses of action open the way for better grid stability, but they also contribute to the environmentally responsible development of the energy industry. FRT strategies will continue to play a crucial role in allowing a more resilient and strong energy future as technology continues to progress and collaborative efforts are continued.

CONCLUSION

It is essential to include Fault Ride Through (FRT) strategies into solar Photovoltaic (PV) systems in order to guarantee the consistency, dependability and smooth functioning of renewable energy sources inside current power grids. In this examination, we looked at a variety of FRT tactics and discussed their relevance, as well as the obstacles and opportunities they provide.

FRT techniques, which include voltage support, current control, active power management and sophisticated control algorithms, play a critical part in the ability of PV systems to ride through grid outages. FRT approaches also play a role in the management of active power. These measures protect both the photovoltaic system and the grid infrastructure, which helps to maintain grid stability and eliminates the possibility of disconnection. Voltage support solutions, which include energy storage systems and reactive power compensation, keep voltage levels steady during failures, which ensures that operations will continue without interruption.

However, there are still obstacles and things to think about when putting FRT strategies into practice. Grid code compliance issues, which arise from the fact that different areas have different standards, call for flexible FRT systems that can accommodate a wide range of requirements. Because of the consequences of the cost of the equipment, it is necessary to strike a careful balance between the advantages of increased FRT capacity and the related financial commitments. Although addressing control complexity concerns is vital for getting the most out of the FRT, doing so requires thorough testing, training and maintenance in order to guarantee system dependability. Concerns about transient reactions bring to light the significance of prompt and accurate system responses under dynamic fault circumstances. This necessitates careful parameter tuning and testing.

The use of FRT in solar photovoltaic systems has some exciting prospects for the future. The combination of artificial intelligence and machine learning offers the opportunity to develop self-learning, predictive FRT techniques that are able to adjust to the circumstances of the grid in real time. The efforts put towards standardization will result in the harmonization of FRT requirements, which will make system design easier and encourage international cooperation. Opportunities for complete fault resilience and optimized response methods may be made available *via* the use of hybrid FRT systems and new control methodologies.

In order to achieve a robust and sustainable energy environment, the development and implementation of effective FRT techniques are required. The renewable energy industry has the potential to improve its fault ride through capacity, contribute to grid stability and speed up the transition towards a cleaner and more dependable energy future if it takes on the challenges that lie ahead, embraces technology breakthroughs as they become available and fosters collaborative efforts.

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