Enhancing Inverter Reliability in Voltage-Controlled Active Distribution Networks with Photovoltaic Integration

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Abstract- - ***As the integration of photovoltaic (PV) systems into voltage-controlled active distribution networks (ADNs) becomes increasingly prevalent, ensuring the reliability of inverters is paramount for stable and efficient energy distribution. This paper explores strategies and advancements aimed at enhancing inverter reliability within the context of voltage-controlled ADNs with PV integration. The investigation encompasses control strategies, fault detection mechanisms, and dynamic adaptability to address challenges such as grid voltage fluctuations and intermittent solar generation. The findings contribute to the understanding of key factors influencing inverter reliability, offering valuable insights for researchers and engineers working towards the optimization of active distribution networks amid the growing adoption of renewable energy technologies.***

Keywords: ***Photovoltaic Integration, Renewable Energy, Power Distribution, Grid Stability, Control Strategies, Fault Detection, Dynamic Adaptability.***

I. INTRODUCTION

Rapid proliferation of solar photovoltaic (PV) systems in distribution networks brings about great challenges to network stability, especially the network voltage control. In an active distribution network (ADN), PV inverters can be utilised to provide reactive power support for voltage regulation, forming a PV inverter based volt/var control (VVC) method. This method is highly promising to defer investments of additional voltage regulation equipment such as capacitor banks, as well as to enhance the networks' capability in hosting more DERs.

However, with the implementation of PV inverter based VVC, a very practical concern emerges, i.e., PV inverter reliability. PV inverters are power electronics devices with high susceptibility to their working conditions and thus relatively short lifespan. The use of PV inverters for further VVC assistance may worsen their dependability, which would reduce the inverter's lifespan and reduce its financial advantages. Therefore, while using PV inverter-based VVC techniques, it is essential to solve the concerns related to PV inverter reliability.

The current energy system is rapidly and profoundly changing from one that is mostly dependent on conventional fossil fuel generation to one that is permeated by a variety of clean energy sources, including hydro, wind, and solar. According to a report by IRENA, the proportion of renewable energy in the increase of worldwide generation capacity in 2021 has reached a record 81%, with around 88% of the new renewable energy capacity coming from solar and wind power [1]. Small-scale solar PV systems close to locations where power is used are referred to as distributed photovoltaics, or DPVs for short. Residential rooftop PV systems are one type of such system. DPVs can also be applied to certain small-scale PV systems that are installed on commercial and industrial properties.

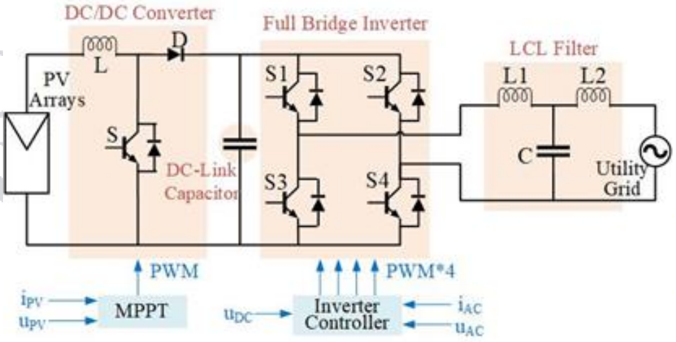

Figure 1: Schematic of a Single-Phase Two-Stage PV Inverter

As an active inverter control strategy for network voltage regulation, PV inverter based VVC aims at optimising and dispatching the var support of PV inverters across the network. Given the vulnerability of PV inverters as well as the potential negative impact of reactive power support Regarding PV inverter dependability, this raises an important question about whether using PV inverters for VVC is ultimately cost-effective. There is a study gap since, unfortunately, none of the VVC works that have been published have addressed problems with PV inverter reliability. It is also unknown how long-term VVC use will affect PV inverter dependability

PV inverter-based VVC makes use of PV inverters to supply extra reactive power support; nevertheless, this extra strain could lead to greater thermal load on PV inverters, which would impair their dependability. However, none of the current VVC models have ever taken into account the importance of PV inverter dependability, which is necessary for both reliable VVC support and sustainable PV energy utilization. Instead, they all primarily concentrate on network voltage management and power loss reduction. In order to do this, the purpose of this subsection is to evaluate PV inverter reliability in relation to the VVC function and explore the incorporation of PV inverter reliability into VVC models.

II. LITEATURE REVIEW

Ding, T., and others [1] By tackling the issue of uncertainty in power flow analysis, you can make a contribution to the field of power systems. The study focuses on interval power flow analysis, which is important for power systems because of the growing integration of renewable energy sources and the unpredictability in their generation that goes along with it. Conventional power flow analysis techniques frequently rely on deterministic values for input parameters; however, more resilient methodologies are required due to uncertainty in renewable energy output and other factors. The study acknowledges and quantifies input parameter uncertainty by using an interval-based method to power flow analysis. This is especially important for power systems that use a lot of renewable energy because those systems' output changes are by nature unpredictable.

Turitsyn, K. et al.[2] make a significant contribution to the power systems sector. The distributed management of reactive power flow inside radial distribution circuits is the main area of interest for Turitsyn et al. Maintaining voltage levels and guaranteeing the stability of power systems depend heavily on reactive power management. The study focuses on situations when photovoltaic (PV) penetration is high. Reactive power management becomes increasingly difficult as renewable energy sources, such PV systems, are integrated into distribution networks since solar generation is intermittent.

M. A. G. de Oliveira and R. A. Shayani [3] Advance knowledge of the difficulties associated with integrating photovoltaic (PV) technology into electricity systems. The IEEE Transactions on Power Systems published the research. The analysis of penetration limits for solar generation within radial distribution systems is the work's main focus. With the growing integration of renewable energy sources like solar photovoltaics into power systems, this is an important factor to take into account. In particular, radial distribution systems are covered in the paper. In distribution networks, radial designs are frequent when electricity travels in a single direction, usually from the substation to the end consumers. It is investigated how PV integration affects these kinds of systems.

B. Das, J. Sharma, and N. Daratha [4] Describe the difficulties in regulating voltage in dispersed generation unbalanced distribution systems. The study's main goal is to investigate techniques for efficient voltage regulation in dispersed generation-based unbalanced distribution systems. For the power supply to remain stable and of high quality, voltage regulation is essential. The coordination of Static Var Compensator (SVC) and On-Load Tap Changer (OLTC) devices is the special subject of the research. Transformer taps are frequently regulated by OLTCs in power systems, while dynamic reactive power support is offered by SVCs. Enhancing voltage control can be achieved by coordinating the actions of various devices.

Power systems is benefited by the work of A. Jafari et al. [5], who optimize switched capacitor scheduling and placement in distribution networks. The authors suggest a two-loop hybrid strategy, which suggests a novel methodology that probably includes various control systems or optimization techniques. Knowing how these loops integrate and interact is essential to the suggested method's efficacy. The study explores the best placements for switched capacitors, stressing the significance of picking key spots inside the distribution network. To achieve the desired gains in voltage control and power factor correction, optimal placement is essential.

Reactive power control techniques for distributed photovoltaic (PV) generators are investigated by Turitsyn et al. [6]. The research primarily focuses on reactive power management techniques and control mechanisms, particularly in distributed solar producers. This is especially important as PV systems and other distributed generation sources proliferate in power networks. The study looks into the different approaches and methods for managing reactive power. Comprehending these alternatives is essential to maximizing PV system performance and guaranteeing their seamless connection with the broader electricity infrastructure. Being published in the esteemed and internationally renowned Proceedings of the IEEE highlights the research's intellectual rigor and technical depth. IEEE Proceedings are renowned for their thorough examinations and assessments of significant subjects in

With a focus on voltage regulation, Zhang et al.'s study [7] examines the It is likely that the research uses quantitative analysis, which may include mathematical formulations, simulations, or optimization models. It is possible to provide numerical outcomes that illustrate the efficacy of

In order to achieve centralized-optimal dispatch of photovoltaic inverters in active distribution networks, Ding et al. [8] present a two-stage resilient optimization approach. The research is primarily concerned with photovoltaic inverter centralized-optimal dispatch. To maximize their performance and contributions, several inverters must be strategically controlled and coordinated within an active distribution network. A two-stage robust optimization strategy is presented in this research. In order to ensure a more robust and dependable dispatch strategy, this methodology probably entails addressing uncertainties or variations in the system at various phases of the dispatch process. The research's conclusions probably apply to active distribution networks, where grid efficiency and stability depend on distributed energy resources operating as best they can, like solar inverters.

Hierarchically-coordinated voltage/VAR regulation in distribution networks employing PV inverters is discussed by Zhang and Xu [9]. The research primarily focuses on voltage/VAR control that is hierarchically coordinated. In order to maximize voltage and reactive power control in distribution networks, this suggests a multi-level control system that probably entails collaboration between multiple organizations. In particular, the application of photovoltaic (PV) inverters to voltage and VAR control is examined in this work. This is especially important since the increasing integration of PV systems into distribution networks affects the dynamics of the system and the controls that are needed. The research's conclusions probably apply to smart grid technologies in general, where sophisticated control techniques are essential for maximizing the performance of distribution networks with dispersed energy supplies.

A two-stage resilient reactive power optimization technique is discussed by Ding et al. [10], taking into account the unpredictable integration of wind power in active distribution networks. The research is primarily focused on reactive power optimization using a two-stage robust optimization approach. This suggests a methodical approach that most likely tackles ambiguities in the various phases of wind power integration, guaranteeing a dependable and robust reactive power optimization plan. In particular, the paper discusses the difficulties posed by uncertain wind power integration. This is important because reactive power management in distribution networks requires sophisticated optimization algorithms due to the inherent variability and uncertainty of wind power. The research's conclusions probably apply to active distribution networks, where incorporating renewable energy sources—like wind power—presents.

III. PROPOSED METHODOLOGY

Model As the emphasis on renewable energy sources has grown, so has the integration of photovoltaic (PV) systems into distribution networks. Inverters are essential for transforming the DC electricity produced by photovoltaic panels into AC power for distribution in voltage-controlled active distribution networks. However, because of the dynamic nature of solar energy output, fluctuations in the grid, and complexity of the distribution network, the dependability of inverters in such systems becomes a critical concern. A thorough study technique is essential to improve inverter reliability in voltage-controlled active distribution networks with solar integration.

Phases such as problem identification, literature review, data gathering, modelling, simulation, analysis, and validation should all be included in the technique. This chapter presents a novel multi-objective VVC optimisation model based on PV inverters. This chapter presents a unique multi-objective PV inverter based VVC optimisation model that develops a Pareto front analysis approach for the proposed model to ensure satisfactory inverter lifetime by incorporating inverter apparent power into the objective function. First, the long-term effects of VVC operation on PV inverter reliability are determined, and the reliability of PV inverters is analyzed by lifespan evaluation of the important components inside inverters. Secondly, a weighted multi-objective PV inverter-based VVC optimisation model is presented, which aims to balance the minimization of apparent power output of the inverter and network power loss. Thirdly, a Pareto front analysis method is used to illustrate the effects of the weighting factor on VVC performance and inverter reliability, allowing an appropriate It is possible to ascertain the weighting factor that will result in the least amount of network power loss by using the expected inverter lifetime. The Pareto front analysis method and the proposed VVC optimization model are validated in a case study.

Topology of PV Inverter

PV inverters are critical power electronic devices for DC-to-AC power conversion as well as supporting the power grid with VVC functions. This chapter applies a typical single-phase two-stage PV inverter for the provision of the VVC function, and the detailed information for this type of inverter, as well as its topology and schematic diagram. This type of inverter is commonly used in small-size distributed PV systems such as rooftop PVs, which are compatible with being aggregated as a large inverter fleet to provide VVC functions for the power grid [22].

Reliability Analysis Models of DC-Link Capacitor

Power devices and the DC-link capacitor are usually the two most fragile components inside a PV inverter, and their lifetimes are two critical factors for inverter reliability assessment [15]. In fact, the lifetimes of power devices and DC-link capacitors are highly dependent on their types and models. In Chapter 3, an IGBT and an aluminium electrolytic capacitor are used as the power device and DC-link capacitor for inverter reliability analysis, and the simulation results verified that the lifetime of the aluminium electrolytic capacitor is lower than the IGBT when used for the VVC function. This chapter applies an aluminium electrolytic capacitor and it is assumed that the inverter operational reliability is determined by the lifetime of the DC-link capacitor [23]. The PV inverter operational reliability can be assessed according to the lifetime evaluation of the DC-link capacitor, via the following steps. Firstly, based on the inverter operating conditions, the capacitor power loss model is applied to obtain the power loss on the capacitor. Secondly, with the obtained power loss, the capacitor thermal model is used to calculate the capacitor core temperature.

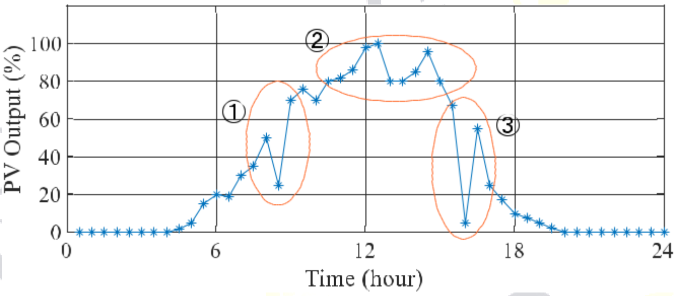

Figure 2 : PV inverter apparent power smoothing mechanism: (a) 24-hour PV power generation profile.

Inverter Power Smoothing

In reality, an inverter power smoothing system is used to meet the inverter reliability restrictions. One way that the inverters in a VVC technique might lessen the variance Reactive power is either injected or absorbed to increase the perceived power output of the inverter. On the other hand, the inverters can be configured to restrict the generation of PV active power to a specific value when needed [17]. When PV active power curtailment and VVC reactive power output are employed, the inverter apparent power smoothing can be applied with a great degree of flexibility. This makes it possible to effectively limit the apparent power output of the inverter using the power smoothing factor. Unlike conventional methods that control active power at the local level to achieve renewable energy smoothing, the proposed power smoothing approach considers a centralized variable voltage controller.

Implementation of PiReCon-VVC

The proposed PiReCon-VVC method with the inverter power smoothing scheme is implemented via a central dispatch manner. The implementation process can be described by the following three key steps. Firstly, the proposed PiReCon-VVC optimisation problem is formulated with the inverter reliability constraints and system-wide information. Secondly, the optimisation problem is solved, and the optimal setpoint decisions of inverter var output and PV curtailment over a dispatch interval are obtained. Thirdly, the signals of optimal setpoint decisions are sent to the inverters in the distribution network, and the inverters change the apparent power outputs to the optimised setpoints. By doing so, both central VVC and inverter power smoothing can be done simultaneously. To guarantee long-term efficient inverter power smoothing, this chapter applies a rolling-horizon based implementation scheme. First, given an optimisation horizon that covers a fixed number of operation time slots, the proposed PiReCon-VVC method is applied to obtain the optimal inverter setpoint decisions. Then, with the proceeding of each operation time slot, new optimisation horizons are formed and the proposed method continues to be applied. The optimised inverter apparent power output at the first time slot of current optimisation horizon is used as the initial apparent power of the next horizon, thus guaranteeing long-term.

IV. RESULT ANALYSIS

VVC Optimisation Result

In this test, simulations are conducted with different settings of the power smoothing factor , to verify the performance of the proposed PiReCon-VVC method. By solving the PiReCon-VVC model (4.43)-(4.51), the inverter active and reactive power outputs of all the PVs are optimised. Figure 4.1 demonstrates the one-year inverter reactive power outputs of PV 4, with as 100% and 20% respectively. as 100% means that the VVC is fully performed without the inverter power smoothing constraints, i.e., the full-VVC case. Note that the positive values of reactive power mean power injection to the network, while negative ones mean absorption.

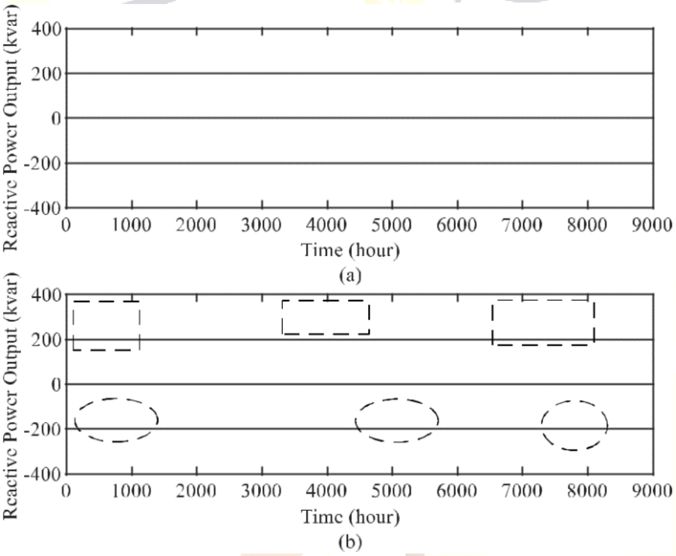

Figure 3 : One-year reactive power outputs of PV 4: (a) Full VVC (=100%); (b) PiReCon-VVC with =20%.

Compared to the full-VVC case in Figure3 (a), the PV inverters with PiReCon-VVC in Figure 3 (b) are utilised to provide some additional reactive power injection for power smoothing, as indicated in the rectangles, and this usually happens during the valleys of inverter apparent power. On the other hand, the inverter reactive power absorption is reduced, as shown in the circles. This is because the reactive power absorption in the VVC usually occurs when the PV power generation is high, leading to the peaks of inverter apparent power. Thus, the less reactive power absorption associated with PV curtailment can effectively reduce the inverter apparent power peaks. This verifies the effectiveness of the proposed PiReCon-VVC method for inverter apparent power smoothing.

Additionally, the one-day inverter apparent power profiles of PV 4 with different values, compared with the no-VVC case, are shown in Figure 4

It can be seen from Figure 5 that prompt var compensation is provided when the PV active power outputs are low, while the PV outputs during PV generation peaks are curtailed. Therefore, the inverter apparent power output is efficiently smoothed by the proposed PiReCon-VVC method. Moreover, the inverter apparent power profile with as 20% is smoother than that with 30%, and this verifies the effectiveness of the proposed power smoothing factor.

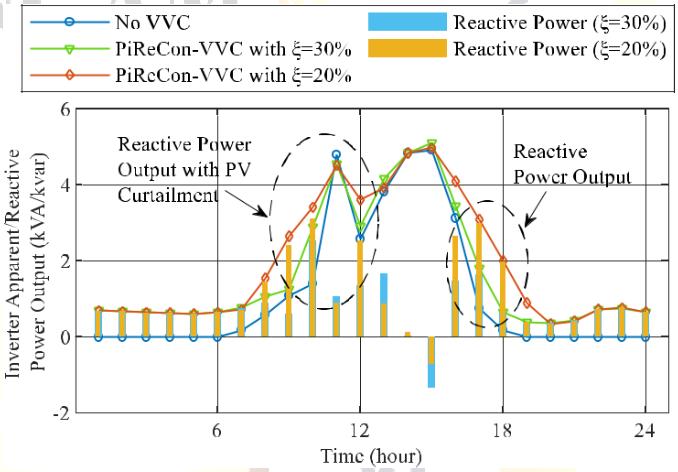

Figure 4 : Inverter apparent/reactive power profiles of PV 4 (on Day 16

Inverter Reliability Analysis Result

The With the optimised inverter power outputs and calculated power loss, the IGBT junction temperature can be obtained from its thermal model. Then, a Rain flow counting technique [19] is applied to transfer the IGBT junction temperature profile into a number of regulated thermal cycles. Each cycle has its own value of junction temperature variation Δ , which is a key factor for inverter lifetime evaluation. Figure 4illustrates the Rain flow counting results of Δ at PV 4 under different cases.

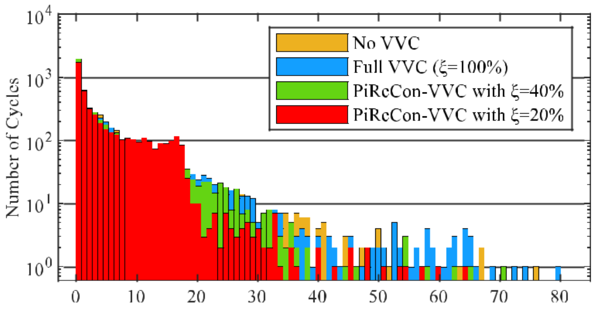

Figure 5: IGBT thermal analysis results of inverters at PV

Compared to the no-VVC case, the IGBT junction temperature variation under the full-VVC case is increased due to the additional use of PV inverters for var compensation. However, with the PiReCon-VVC method, the temperature variation is effectively reduced by the proposed inverter reliability constraints for power smoothing. Besides, a lower power smoothing factor can achieve better performance in reduction of the junction temperature variation. The inverter lifetime evaluation is then conducted based on the IGBT life model [16]. The inverter lifetimes with different values at selected PVs are demonstrated in Figure 5.

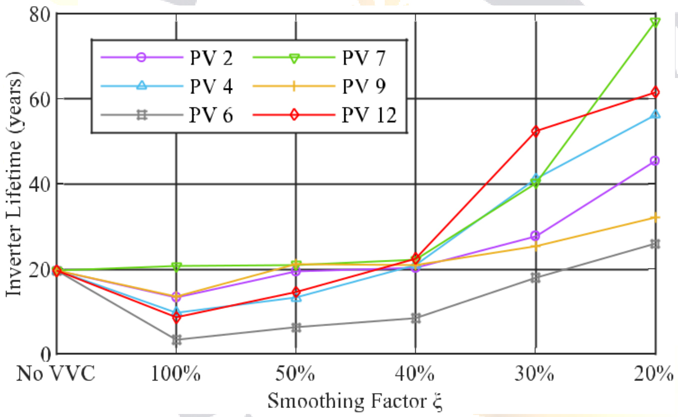

Figure 6: Inverter lifetimes based on IGBT lifetime evaluation with different values at selected PVs.

In this figure, due to the same PV output profile and ambient temperature, the inverter lifetimes without VVC at all the PVs are calculated as the same 19.6 years. Under the full-VVC case (=100%), almost all the inverter lifetimes are reduced, due to the severer junction temperature variation caused by the inverter use for VVC. When applying the proposed PiReCon-VVC method with inverter power smoothing, the inverter lifetime reduction can be efficiently mitigated. Especially when the power smoothing factor approaches 30%, the inverter lifetimes are significantly enhanced, which can be even higher than those under the no-VVC case.

Validation of Computing Efficiency

In this research, the proposed PiReCon-VVC method is implemented for one year. In each optimisation horizon, the PiReCon-VVC optimisation problem is iteratively solved by the developed penalty CCP until convergence. Via simulations, the convergence of the penalty CCP is validated, i.e., the gap can be always reduced into the specified tolerance. Figure 7 visualises the convergence process of the penalty CCP with different power smoothing factors for one optimisation horizon.

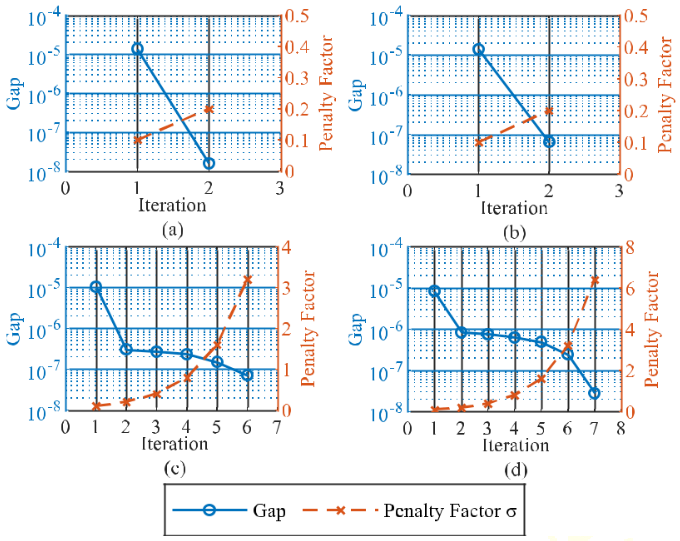

Figure 7: Convergence process of penalty CCP with power smoothing factor as: (a) 50%; (b) 40%; (c) 30%; (d) 20%.

V. CONCLUSION

The Considering the importance of PV inverter reliability in VVC-featured ADNs, this chapter proposes a PiReCon-VVC method with inverter power smoothing under uncertainties. Based on the inverter reliability analysis, new reliability constraints are proposed with a power smoothing factor to constrict the inverter apparent power variation and a PV curtailment scheme to facilitate the power smoothing. Then, with the proposed reliability constraints, a scenario-based stochastic VVC optimisation model is formed to minimise the power losses. Moreover, a CCP programming method is developed to solve the proposed non-convex PiReCon-VVC optimisation problem.

Via the comprehensive case study, the simulation results verify that the proposed PiReCon-VVC method can efficiently minimise the power losses, while guaranteeing or even enhancing the PV inverter reliability. Besides, the developed CCP method is validated with high computing efficiency.The research identifies that the development and implementation of adaptive control strategies for inverters play a crucial role in addressing voltage fluctuations introduced by PV integration and grid variations. Advanced control algorithms and optimization techniques contribute to dynamic response capabilities. The research reveals that enhancing fault tolerance mechanisms within inverters is essential for maintaining robust performance during grid disturbances or internal component failures. Strategies such as redundancy and protective measures significantly mitigate the impact of faults.The research emphasizes the importance of lifecycle analysis for inverter components. Proactive maintenance strategies based on degradation patterns extend the lifespan of inverters, reducing unexpected failures and downtime. Evaluating and optimizing communication protocols among inverters and the distribution network is critical. The research underscores the need for secure, reliable communication channels to facilitate effective coordination and response to voltage-related issues. Integrating predictive analytics and machine learning algorithms enhances the capability to forecast potential issues in inverter performance. This integration enables proactive maintenance and improves the overall reliability of the system.

REFERENCES

[1] . Ding et al., "Interval Power Flow Analysis Using Linear Relaxation and Optimality-Based Bounds Tightening (OBBT) Methods," IEEE Trans. Power Syst., vol. 30, no. 1, pp. 177-188, Jan. 2015.

[2] K. Turitsyn, P. Šulc, S. Backhaus and M. Chertkov, "Distributed control of reactive power flow in a radial distribution circuit with high photovol- taic penetration," IEEE PES Gen. Meeting, Providence, RI, 2010, pp. 1-6.

[3] R. A. Shayani and M. A. G. de Oliveira, "Photovoltaic Generation Pene- tration Limits in Radial Distribution Systems," IEEE Trans. Power Syst., vol. 26, no. 3, pp. 1625-1631, Aug. 2011.

[4] N. Daratha, B. Das and J. Sharma, "Coordination Between OLTC and SVC for Voltage Regulation in Unbalanced Distribution System Distrib- uted Generation," IEEE Trans. Power Syst., vol. 29, no. 1, pp. 289-299, Jan. 2014.

[5] A. Jafari, H. Ganjeh Ganjehlou, T. Khalili, B. Mohammadi-Ivatloo, A. Bidram and P. Siano, "A Two-Loop Hybrid Method for Optimal Place- ment and Scheduling of Switched Capacitors in Distribution Networks," IEEE Access, vol. 8, pp. 38892-38906, 2020.

[6] K. Turitsyn, P. Sulc, S. Backhaus and M. Chertkov, "Options for Control of Reactive Power by Distributed Photovoltaic Generators," Proc. IEEE, vol. 99, no. 6, pp. 1063-1073, June 2011.

[7] Y. Zhang, Y. Xu, H. Yang and Z. Dong, "Voltage regulation-oriented co- planning of distributed generation and battery storage in active distribu- tion networks," Int. J. Elec. Power and Energy Syst., vol. 105, pp. 79-88, Feb. 2019.

[8] T. Ding, C. Li, Y. Yang, J. Jiang, Z. Bie and F. Blaabjerg, "A Two-Stage Robust Optimization for Centralized-Optimal Dispatch of Photovoltaic Inverters in Active Distribution Networks," IEEE Trans. Sustain. Energy, vol. 8, no. 2, pp. 744-754, April 2017.

[9] C. Zhang and Y. Xu, "Hierarchically-Coordinated Voltage/VAR Control of Distribution Networks Using PV Inverters," IEEE Trans. Smart Grid., vol. 11, no. 4, pp. 2942-2953, July 2020.

[10] T. Ding, S. Liu, W. Yuan, Z. Bie and B. Zeng, "A Two-Stage Robust Re- active Power Optimization Considering Uncertain Wind Power Integra- tion in Active Distribution Networks," IEEE Trans. Sustain. Energy, vol. 7, no. 1, pp. 301-311, Jan. 2016.

[11] L. Wang, R. Yan, F. Bai, T. Saha and K. Wang, "A Distributed Inter- Phase Coordination Algorithm for Voltage Control With Unbalanced PV Integration in LV Systems," IEEE Trans. Sustain. Energy, vol. 11, no. 4, pp. 2687-2697, Oct. 2020.

[12] A. Singhal, V. Ajjarapu, J. Fuller and J. Hansen, "Real-Time Local Volt/Var Control Under External Disturbances With High PV Penetra- tion," IEEE Trans. Smart Grid, vol. 10, no. 4, pp. 3849-3859, July 2019.

[13] C. Zhang, Y. Xu, Z. Dong, and J. Ravishankar, "Three-Stage Robust In- verter-Based Voltage/Var Control for Distribution Networks With High- Level PV," IEEE Trans. Smart Grid., vol. 10, no. 1, pp. 782-793, Jan. 2019.

[14] C. Zhang, Y. Xu, Z. Y. Dong and R. Zhang, "Multi-Objective Adaptive Robust Voltage/VAR Control for High-PV Penetrated Distribution Net- works," IEEE Trans. Smart Grid., vol. 11, no. 6, pp. 5288-5300, Nov. 2020.

[15] J. Li, Z. Xu, J. Zhao and C. Zhang, "Distributed Online Voltage Control in Active Distribution Networks Considering PV Curtailment," IEEE Trans. Ind. Informat., vol. 15, no. 10, pp. 5519-5530, Oct. 2019.

[16] A. Golnas, "PV System Reliability: An Operator's Perspective," IEEE Journal of Photovoltaics, vol. 3, no. 1, pp. 416-421, Jan. 2013.

[17] M. Schmela, "PHOTON: Inverter survey 2012 stats," Presentation at the PHOTON’s 3rd PV Inverter Conference, San Francisco, Feb. 2012.

[18] A. Anurag, Y. Yang, and F. Blaabjerg, "Thermal performance and relia- bility analysis of single-phase PV inverters with reactive power injection outside feed-in operating hours," IEEE Trans. Emerg. Sel. Topics Power Electron., vol. 3, no. 4, pp. 870-880, Dec. 2015.

[19] A. Sangwongwanich, Y. Yang, D. Sera and F. Blaabjerg, "Mission Pro- file-Oriented Control for Reliability and Lifetime of Photovoltaic Invert- ers," IEEE Trans. Ind. Appl., vol. 56, no. 1, pp. 601-610, Jan.-Feb. 2020.

[20] Y. Yang, A. Sangwongwanich and F. Blaabjerg, "Design for reliability of power electronics for grid-connected photovoltaic systems," CPSS Trans. Power Electronics and Applications, vol. 1, no. 1, pp. 92-103, Dec. 2016.

[21] H. Huang and P. A. Mawby, "A Lifetime Estimation Technique for Volt- age Source Inverters," IEEE Trans. Power Electron., vol. 28, no. 8, pp. 4113-4119, Aug. 2013.

[22] M. Held, P. Jacob, G. Nicoletti, P. Scacco and M. H. Poech, "Fast power cycling test of IGBT modules in traction application," in Proc. Int. Conf. Power Electron. Drive Syst., Singapore, 1997, pp. 425-430, vol. 1.

[23] K. Ma, M. Liserre, F. Blaabjerg and T. Kerekes, "Thermal Loading and Lifetime Estimation for Power Device Considering Mission Profiles in Wind Power Converter," IEEE Trans. Power Electron., vol. 30, no. 2, pp. 590-602, Feb. 2015.

[24] H. Wang and F. Blaabjerg, "Reliability of Capacitors for DC-Link Appli- cations in Power Electronic Converters—An Overview," IEEE Trans. Ind. Appl., vol. 50, no. 5, pp. 3569-3578, Sept.-Oct. 2014.

[25] L. Wei, J. McGuire and R. A. Lukaszewski, "Analysis of PWM Frequency Control to Improve the Lifetime of PWM Inverter," IEEE Trans. Ind. Appl., vol. 47, no. 2, pp. 922-929, March-April 2011.

[26] U. Choi, S. Jørgensen and F. Blaabjerg, "Advanced Accelerated Power Cycling Test for Reliability Investigation of Power Device Modules," IEEE Trans. Power Electron., vol. 31, no. 12, pp. 8371-8386, Dec. 2016.

[27] M. Miner, "Cumulative fatigue damage," Journal of applied mechanics, vol. 12, no. 3, pp. A159-A164, 1945.

[28] X. Pei, W. Zhou, and Y. Kang, "Analysis and Calculation of DC-Link Current and Voltage Ripples for Three-Phase Inverter With Unbalanced Load," IEEE Trans. Power Electron., vol. 30, no. 10, pp. 5401-5412, Oct. 2015.

[29] T. Khalili, S. Nojavan, and K. Zare, "Optimal performance of microgrid in the presence of demand response exchange: A stochastic multi-objec- tive model," Computers & Electrical Engineering, vol. 74, pp. 429-450, Mar. 2019.

[30] M. Erol-Kantarci and H. T. Mouftah, "Energy-Efficient Information and Communication Infrastructures in the Smart Grid: A Survey on Interac- tions and Open Issues," IEEE Commun. Surveys Tuts., vol. 17, no. 1, pp. 179-197, Firstquarter 2015.