

Reactive voltage control strategy of distribution network considering the reliability of photovoltaic power supply

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Abstract. Photovoltaic power actively regulates the reactive power of the active distribution network, leading to the increase of output current of the photovoltaic inverter. Consequently, the temperature rise significantly impacts the maximum junction temperature of the Insulated Gate Bipolar Transistor (IGBT), leading to fluctuations in the junction temperature. To realize the active support of the reactive power of the photovoltaic power supply and ensure its reliable operation, a reactive voltage control strategy of the active distribution network considering the reliability of the photovoltaic power supply is proposed. Considering the reactive power support capability of the distributed photovoltaic power, a multi-objective reactive power optimization model for active distribution networks is established based on IGBT maximum junction temperature, distribution network losses, and photovoltaic active power reduction. The effectiveness of the proposed strategy in enhancing the minimum lifetime, average lifetime, and reliability of photovoltaic power sources is verified using the IEEE 33-node standard distribution system. The results show that under the strategy proposed in this paper, the average junction temperature and junction temperature fluctuation of IGBT are effectively reduced, and the minimum lifetime and average lifetime of all IGBTs are increased by 8 years and 4 years respectively.

Keywords: Photovoltaic inverter, IGBT junction temperature, IGBT reliability, Reactive power optimization, Active distribution network.

Nomenclature

		ΔT_j	The junction temperature fluctuation of IGBT under steady-state junction temperature
$P_{T,con}^{loss}$	The conduction loss		
$P_{T,sw}^{loss}$	The breaking loss	T_{jmin}	The minimum junction temperature under steady-state junction temperature
δ_t	The duty factor	t_{on}	The duration required for the power cycle
x_i	The i th data input	I	The current flowing through the bonding wire
i_p	The current passing through IGBT	D	The diameter of the bonding wire
T_j	The IGBT junction temperature	U	The blocking voltage
f_{sw}	The turn-on and turn-off frequency of IGBT module	n_i	The number of temperature cycles under thermal load
T_{amb}	Ambient temperature	N_f^i	The number of cycle failures associated with the i th junction temperature fluctuation
P_T^{loss}	The power loss of IGBT	β	The scale parameter of the Weibull distribution
P_D^{loss}	The power loss of anti-parallel diode	η	The shape parameter of the Weibull distribution
Z_{tjh}	Thermal impedance parameters in the Foster model	S_{max}	The rated apparent power of the photovoltaic inverter
N_f	The number of thermal cycles before IGBT failure	P_{PV}	The active power output of the photovoltaic inverter

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$Q_{\max}$	The reactive output limit of the photovoltaic inverter
U_{AC}	The effective value of the inverter AC-side voltage
Q_{PV}	The reactive output of the photovoltaic inverter
f	The goal function of the reactive power optimization model
$\omega_1, \omega_2, \omega_3$	The weight coefficients of the goal function
B	The distribution network bus number set
$P_{\text{net,loss}}$	The active distribution network loss
$P_{\text{curt,loss}}$	The amount of photovoltaic active power reduction
$P_{PV,c\ k(t)}$	The active power reduction of photovoltaic power supply at bus k at time t
$T_{\text{IGBT_max}}$	The maximum junction temperature during the IGBT junction temperature fluctuation period
r_{jk}	The line resistance from bus j to bus k
$I_{jk}(t)$	The line current from bus j to bus k at time t
$P_k^{\text{PV}}(t)$	The output active of photovoltaic power supply at bus k at time t
K	The number set of distributed photovoltaic nodes connected to the active distribution network
$Q_k^{\text{inv}}(t)$	The reactive output of photovoltaic power supply at bus k at time t
j, k, l	The bus index
$J(k)$	The parent nodes
$L(k)$	The child nodes
$U_{\max}$	The upper limits of the grid voltage
$U_{\min}$	The lower limits of the grid voltage
S_k^{cap}	The photovoltaic capacity at busbar k

1 Introduction

With the world's population increasing in lockstep with technological and industrial advancements, as well as the increasing demand for energy supplies in various industries to meet the population's needs, the use of renewable energies such as photovoltaic power has become unavoidable, even more so given the expected depletion of traditional energy sources [1]. Photovoltaic power generation is characterized by stochasticity and volatility. Large-scale photovoltaic systems connected to the active distribution network can lead to problems such as node voltage overruns and distribution network current reversal [2]. Usually, reactive power regulation equipment such as on-load tap transformers and static reactive power compensators can be adjusted to stabilize the distribution network node voltage and reduce the distribution network active losses [3], but their response speed is slow. Lately, the role of photovoltaic power supply in offering support for reactive power and compensating harmonic currents has been receiving

increasing interest. Reactive power support from photovoltaic sources can significantly reduce the reactive power equipment deployment costs for distribution networks while simultaneously enhancing the operational stability of the distribution network.

The optimization of distribution network reactive power can be categorized into three types: centralized optimization, distributed optimization, and decentralized optimization [4]. The centralized optimization of the distribution network usually takes the network loss and voltage offset of the active distribution network as the optimization objectives, using heuristic algorithms such as the genetic algorithm and differential evolution algorithm [5–7] to solve the problem. However, heuristic algorithms are time-consuming to solve the problem and difficult to apply online. The model for optimizing reactive power in the active distribution network, originally nonlinear and nonconvex, is converted into a Second-Order Cone Programming (SOCP) model through the process of linearization and second-order cone relaxation [8, 9]. This transformation enhances the solving speed of the reactive power optimization model, although the constraint relaxation needs to satisfy certain constraints. Different from the centralized optimization, the distributed optimization of the distribution network usually divides the distribution network first. There is some information transmission between these districts and the sub-optimization problem is solved within each district, which reduces the computational complexity and relieves the communication pressure. The active distribution network distributed optimization can be achieved through the application of both the alternating direction multiplier method and the dual decomposition method [10, 11]. In the decentralized reactive power optimization mode, the dispatching center participates in partial optimal operation. Each distributed power source collects local operation information and interacts with adjacent distributed power sources, which accelerates the speed of control and reduces the calculation amount and communication pressure of the dispatching center [12].

As the distribution network's node count and reactive voltage control device quantity rise, the complexity of the reactive power optimization model experiences exponential growth. This leads to a sluggish solution process and diminished real-time performance in reactive power optimization. Data-driven methods represented by machine learning, deep learning, and deep reinforcement learning have attracted much attention because of their advantages in real-time and fast optimization model solving. Literature [13] uses a multiagent reinforcement learning approach to achieve reactive power optimization in the active distribution network. The reactive power optimization problem is transformed into a Markov decision process, and a centralized training and decentralized execution framework is used to train multi-agents for fast implementation of distributed reactive power voltage optimization in the active distribution network. The reactive power optimization in the active distribution network is accomplished through the utilization of deep learning principles [14]. It uncovers the nonlinear relationship between the optimal reactive

power output of the distribution network and its operational state based on deep belief networks. This makes the model solution faster when the centralized optimization method is applied to the distribution network. However, existing distribution network reactive power optimization strategies that consider reactive power regulation of photovoltaic power sources do not take into account the impact of reactive power output from photovoltaic inverters on their operational lifetime and reliability.

At present, the primary emphasis in the analysis of photovoltaic inverter reliability lies in examining the reliability of the Insulated Gate Bipolar Transistor (IGBT) components housed within the photovoltaic inverters [15]. For assessing the operational life and reliability of the IGBT power device, a commonly employed method is the statistically based approach. This approach models the IGBT operational lifetime and reliability by assuming a constant failure rate based on statistical data manuals, such as MIL-HDBK-217F [16].

Nevertheless, as power electronics technology continues to advance and mature, the operating limits of modern power converters are expanded into the wear area [17, 18], resulting in the traditional method of modeling with a constant failure rate is no longer applicable. In recent years, methods for lifespan assessment based on physical failure mechanisms have gained increasing attention. Among them, lifespan assessment methods based on analytical lifespan models have garnered widespread interest. [19]. Research has demonstrated that the mission profiles have a direct impact on the lifetime and reliability of IGBTs in photovoltaic inverters [20, 21]. The IGBT lifespan assessment process based on mission profiles typically consists of three steps: Initially, the IGBT junction temperature is calculated based on the mission profile. Then, thermal load statistics are generated based on the IGBT junction temperature information. Finally, the IGBT lifespan is estimated using an analytical lifespan model and the Miner rule. Additionally, considering the stochastic nature of lifespan models and device parameters, the Monte-Carlo simulation method is used to randomly sample 10,000 instances, resulting in a distribution of lifespans for power devices like IGBTs. The lifespan corresponding to 10% unreliability is typically used as the evaluation lifespan for IGBTs [22, 23]. Given the reactive output capability of the photovoltaic inverter, the impact of the reactive output generated by the photovoltaic inverter on its life expectancy and dependability is studied in [24, 25]. It is noticed that there exists a high-positive correlation between the reactive output and the maximum, fluctuation of the IGBT junction temperature. There is a negative correlation relationship between the reactive output and the life expectancy, and operation dependability of the photovoltaic inverter. Ultra voltage/reactive resulting from photovoltaic inverter may cause immature invalidation of photovoltaic power generation system and thus harm the stable and economic operation of the distribution network [26]. Therefore, when carrying out voltage/reactive optimization, there exists the necessity to take into account the impact of reactive output generated by distributed photovoltaic power supply on the life expectancy and dependability of IGBT. It is pointed out in [27] that the

junction temperature of IGBT is a crucial indicator to assess the life expectancy and dependability of power switches. Smoothing the junction temperature undulation and decreasing the amplitude of junction temperature can enormously prolong the life expectancy and dependability of IGBT and other switches [28]. Consequently, the junction temperature of IGBT and other power devices is supposed to be weighted and studied in voltage/reactive optimization of photovoltaic high permeability active distribution network.

Inspired by the aforementioned issues, the innovation of this paper is to consider the reliability of photovoltaic inverter while considering the participation of photovoltaic inverter in reactive power and voltage control of distribution network. Firstly, this paper employs a reliability assessment method based on mission profiles for IGBTs to quantitatively assess the reliability of IGBTs in photovoltaic power systems. The voltage/reactive optimization model of active distribution network considering the dependability of photovoltaic power supply is established. The IGBT junction temperature of photovoltaic inverter is brought in the voltage/reactive optimization target of active distribution network. The nonlinear non-convex model is described as a second-order cone programming model through linearizing and second-order cone relaxing to elevate the model-solving efficiency. Finally, the IEEE 33-node distribution system and the actual distribution network system in a certain area are used for example verification.

2 IGBT reliability evaluation based on mission profile

To take into account the dependability of photovoltaic power supply while regulating the reactive voltage of active distribution network, it is necessary to quantify and evaluate the dependability of photovoltaic power supply. Then a voltage/reactive optimization model of the distribution network taking into account the dependability of photovoltaic power supply can be established on this basis. The reliability of photovoltaic power provision is significantly influenced by the IGBT component, with IGBT-related malfunctions contributing to over 30% of total photovoltaic inverter failures [29]. The lifetime expectancy and dependability appraisal of photovoltaic power supply can focus on the life expectancy and dependability appraisal of IGBT. The dependability appraisal process of IGBT based on the mission profile is displayed in Figure 1.

The junction temperature of the IGBTs is first calculated based on the thermoelectric coupling model, and then the heat load information of the IGBTs is recorded using the rain flow counting method.

The amount of invalidation circulations is computed by IGBT life expectancy model. Additionally, the lifetime expectancy damage of IGBT is evaluated in the light of the Miner criterion. Taking into consideration the potential discrepancies in device parameters, the life expectancy distribution of Insulated Gate Bipolar Transistors (IGBTs)

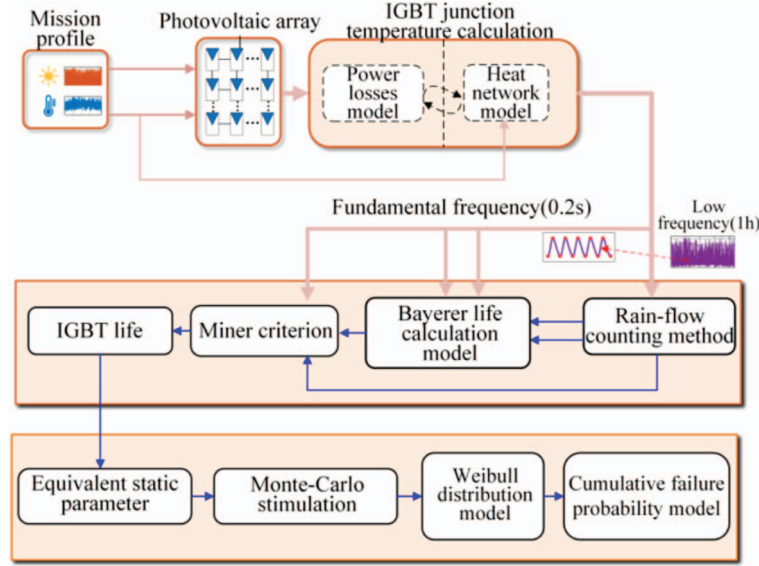


Fig. 1. IGBT reliability evaluation process considering the effect of fundamental (or low frequency) junction temperature.

can be gained through Monte-Carlo simulation. By fitting the two parameters Weibull distribution, the Weibull probability density function that conforms to the IGBT life expectancy distribution can be derived. In addition, the probability density function of the lifetime distribution is integrated to obtain the Weibull cumulative distribution function. Ultimately, a quantitative analysis of IGBT reliability can be conducted.

2.1 IGBT junction temperature computing

The module loss of IGBT P_T^{loss} mainly includes conduction loss and breaking loss, the equation is expressed as:

$$P_T^{\text{loss}} = P_{T,\text{con}}^{\text{loss}} + P_{T,\text{sw}}^{\text{loss}}, \quad (1)$$

$$P_{T,\text{con}}^{\text{loss}} = i_p(V_{\text{CE},25^\circ\text{C}} + K_{V,T}(T_j - 25))\delta(t) + i_p^2(r_{\text{CE},25^\circ\text{C}} + K_{r,T}(T_j - 25))\delta(t), \quad (2)$$

$$P_{T,\text{sw}}^{\text{loss}} = f_{\text{sw}}E_{\text{sw}}(i_p)K_1(U_{\text{dc}})K_2(R_g)(1 + K_{\text{sw}}(125 - T_j)), \quad (3)$$

where $P_{T,\text{con}}^{\text{loss}}$, $P_{T,\text{sw}}^{\text{loss}}$ are the conduction loss and breaking loss of IGBT severally, δ_t is the duty factor, i_p is the current passing through IGBT, T_j is the IGBT junction temperature, $V_{\text{CE},25^\circ\text{C}}$, $r_{\text{CE},25^\circ\text{C}}$, $K_{V,T}$, $K_{r,T}$, K_{sw} , $K_1(U_{\text{dc}})$, $K_2(R_g)$ are the conduction and breaking loss parameters which can be obtained from the datasheet of IGBT, f_{sw} is the turn-on and turn-off frequency of IGBT module.

The Foster model and the model for power loss are used for the electrothermal conversion of IGBT, and the power loss profile is converted into a thermal stress profile. It can be described as:

$$T_j = Z_{\text{tjh}}P_T^{\text{loss}} + Z_{\text{ha}}(P_T^{\text{loss}} + P_D^{\text{loss}}) + T_{\text{amb}}, \quad (4)$$

where T_{amb} is ambient temperature, P_T^{loss} and P_D^{loss} are the power loss of IGBT and anti-parallel diode, and Z_{tjh} and Z_{ha} are thermal impedance parameters in the Foster model.

2.2 IGBT lifetime assessment

In this paper, the Bayerer model as the chosen approach is to conduct a lifetime assessment [30, 31]. The theoretical framework can be represented as:

$$N_f = A(\Delta T_j)^{\beta_1} e^{\beta_2/(T_{\text{jmin}}+273)} t_{\text{on}}^{\beta_3} I^{\beta_4} U^{\beta_5} D^{\beta_6}, \quad (5)$$

where N_f is the number of thermal cycles before IGBT failure, ΔT_j is the junction temperature fluctuation of IGBT under steady-state junction temperature, T_{jmin} is the minimum junction temperature under steady-state junction temperature, t_{on} is the duration required for the power cycle, I is the current flowing through the bonding wire, D is the diameter of the bonding wire, U is the blocking voltage, A and β_1 – β_6 are Bayerer model parameters.

Lifetime consumption refers to the lifetime loss over the lifespan of power devices. Considering the low-frequency junction temperature, the lifetime consumption of the power device is represented as:

$$L_{\text{low}} = \sum_i \frac{n_i}{N_f^i}, \quad (6)$$

where n_i represents the number of temperature cycles under thermal load, and N_f^i represents the number of cycle failures associated with the i th junction temperature fluctuation.

For the fundamental junction temperature, assuming that the sampling period of solar irradiance and ambient temperature is m (min/sampling point), the lifetime consumption of each sampling period at the fundamental junction temperature can be calculated:

$$L_{\text{fun}} = \sum_i \frac{50 \times 60m}{N_f^i}. \quad (7)$$

The Miner linear cumulative damage criterion states that the device damage may occur in each temperature cycle, and this damage accumulates linearly. According to LC criterion, the power device will fail if the cumulative damage exceeds 1.

2.3 IGBT reliability evaluation

The distribution of IGBT lifetime is determined through Monte-Carlo simulation, and the scale and shape parameters of the two-parameter Weibull distribution are obtained by fitting the data. Then the Weibull probability density function of IGBT lifetime can be received as follows:

$$f(x) = \frac{\beta}{\eta^\beta} x^{\beta-1} \exp\left(-\left(\frac{x}{\eta}\right)^\beta\right), \quad (8)$$

where β is the scale parameter of the Weibull distribution, η is the shape parameter of the Weibull distribution, and x is the IGBT running time.

The cumulative distribution function, derived from the integration of the probability density function of IGBT lifetime distribution to assess power device unreliability is as follows:

$$F(x) = \int_0^x f(x)dx = 1 - e^{-\left(\frac{x}{\eta}\right)^\beta}. \quad (9)$$

3 Volt/var control strategy of active distribution network considering the reliability of photovoltaic power supply

3.1 Photovoltaic reactive power support capacity

Generally, the design of photovoltaic inverters has a certain capacity margin, which makes it have fast and flexible reactive support capability and can participate in the reactive power and voltage regulation of active distribution network. The grid-deliverable reactive power from the photovoltaic inverter relies on the inverter's rated apparent power and active output. The reactive output limit of a photovoltaic inverter is related to its rated apparent power and active output and can be expressed as:

$$Q_{\text{max}} = \sqrt{S_{\text{max}}^2 - P_{\text{PV}}^2}, \quad (10)$$

where S_{max} is the rated apparent power of the photovoltaic inverter, P_{PV} is the active power output of the

photovoltaic inverter, and Q_{max} is the reactive output limit of the photovoltaic inverter.

When the reactive output of the photovoltaic inverter is 0, the IGBT current in the photovoltaic inverter is given as:

$$i_p = \frac{\sqrt{2}P_{\text{PV}}}{U_{\text{AC}}}, \quad (11)$$

where U_{AC} is the effective value of the inverter AC-side voltage.

When the photovoltaic inverter's reactive power output is non-zero, the apparent power S and the IGBT current i_p of the photovoltaic inverter can be expressed as follows:

$$S = \sqrt{P_{\text{PV}}^2 + Q_{\text{PV}}^2}, \quad (12)$$

$$i_p = \frac{\sqrt{2}S}{U_{\text{AC}}}, \quad (13)$$

where Q_{PV} is the reactive output of the photovoltaic inverter.

Based on equations (11) and (13), when the photovoltaic inverter participates in reactive power compensation with a fixed active output, the apparent power and output current of the inverter increase. Consequently, this results in an elevation of the IGBT junction temperature, leading to a decrease in the IGBT lifetime and reliability in photovoltaic inverters.

3.2 Reactive power optimization model of active distribution network considering the reliability of photovoltaic power supply

In order to ensure the reliable operation of the photovoltaic inverter, the effect of its reactive power support on the IGBT junction temperature must be considered. This factor should be taken into account during reactive power optimization of the active distribution network in order to maintain its safety and stability. The reactive power optimization model of the distribution network is established with the objectives of active loss of distribution network lines, reduction of active power by photovoltaic inverters, and highest junction temperature of photovoltaic inverter IGBT:

$$\min f = \omega_1 P_{\text{net,loss}} + \omega_2 P_{\text{curt,loss}} + \omega_3 T_{\text{IGBT,max}}, \quad (14)$$

$$P_{\text{net,loss}} = \sum_{j,k \in B} r_{jk} I_{jk}^2(t), \quad (15)$$

$$P_{\text{curt,loss}} = \sum_{k \in K} P_k^{\text{PV},c}(t), \quad (16)$$

$$T_{\text{IGBT,max}} = f(P_k^{\text{PV}}(t), Q_k^{\text{inv}}(t), T_{\text{amb},k}(t), \quad (17)$$

where f is the goal function of the reactive power optimization model, ω_1 , ω_2 , ω_3 are the weight coefficients of

the goal function, B is the distribution network bus number set, $P_{\text{net,loss}}$ is the active distribution network loss, $P_{\text{curt,loss}}$ is the amount of photovoltaic active power reduction, $P_k^{\text{PV},c}(t)$ is the active power reduction of photovoltaic power supply at bus k at time t , $T_{\text{IGBT_max}}$ is the maximum junction temperature during the IGBT junction temperature fluctuation period, r_{jk} is the line resistance from bus j to bus k , $I_{jk}(t)$ is the line current from bus j to bus k at time t , $P_k^{\text{PV}}(t)$ is the output active of photovoltaic power supply at bus k at time t , K is the number set of distributed photovoltaic nodes connected to the active distribution network, $Q_k^{\text{inv}}(t)$ is the reactive output of photovoltaic power supply at bus k at time t , $T_{\text{amb},k}(t)$ is the ambient temperature at bus k at time t .

The optimization of reactive power in an active distribution network must adhere to various constraints, including distribution network power flow, bus voltage limits, line current limits, and photovoltaic inverter capacity restrictions, among others. The constraints of the distribution network reactive power optimization model considering the reliability of photovoltaic supply are as follows:

$$P_k^{\text{PV}}(t) - P_k^L(t) = \sum_{l \in L(k)} P_{kl}(t) - \sum_{j \in J(k)} (P_{jk}(t) - r_{jk} I_{jk}^2(t)), \quad (18)$$

$$Q_k^{\text{inv}}(t) - Q_k^L(t) = \sum_{l \in L(k)} Q_{kl}(t) - \sum_{j \in J(k)} (Q_{jk}(t) - x_{jk} I_{jk}^2(t)), \quad (19)$$

$$U_k^2(t) = U_{j,k}^2(t) - 2(r_{jk} P_{jk}(t) + x_{jk} Q_{jk}(t)) + (r_{jk}^2 + x_{jk}^2) I_{jk}^2(t), \quad (20)$$

$$I_{jk}^2(t) = \frac{P_{jk}^2(t) + Q_{jk}^2(t)}{U_j^2(t)}, \quad (21)$$

$$U_{\min} \leq U_k(t) \leq U_{\max}, \quad (22)$$

$$0 \leq I_{jk}(t) \leq I_{jk}^{\max}, \quad (23)$$

$$\sqrt{(P_k^{\text{PV}}(t))^2 + (Q_k^{\text{inv}}(t))^2} \leq S_k^{\text{cap}}, \quad (24)$$

$$0 \leq P_k^{\text{PV}}(t) \leq P_k^{\text{PV},m}(t), \quad (25)$$

$$P_k^{\text{PV},c}(t) = P_k^{\text{PV},m}(t) - P_k^{\text{PV}}(t), \quad (26)$$

where j , k , l are the busbar index, $J(k)$ and $L(k)$ represent parent and child nodes, respectively. x_{jk} is the inductance from busbar j to busbar k , $P_k^L(t)$, $Q_k^L(t)$ and $U_k(t)$ are the active load, reactive load, and bus voltage of bus k at time t , respectively. $P_{jk}(t)$ and $Q_{jk}(t)$ are the active and reactive power from busbar j to busbar k , respectively. $I_{jk}^{\max}$ is a

superior limit of I_{jk} between busbar j and busbar k , $U_{\max}$ and $U_{\min}$ are the upper and lower limits of the grid voltage. S_k^{cap} is solar photovoltaic capacity at busbar k , $P_k^{\text{PV},m}$ is active power output at busbar k based on the maximum power tracking control.

3.3 Second-order cone programming model for reactive power optimization of distribution network

The optimization of reactive power in distribution network systems considering the dependability of photovoltaic power supply is a nonlinear non-convex model, which can be tackled by heuristic algorithms such as genetic algorithm and differential evolution algorithm. However, the heuristic algorithm requires a lot of cyclic calculations and takes a long time to solve. For the convenience of subsequent analysis of IGBT lifetime and reliability under the annual mission profile, it is necessary to enhance the speed of solving the optimization model. This paper will consider the nonlinear part linearization and second-order cone relaxation in the reactive power optimization model considering the reliability of photovoltaic power supply, simplify the model-solving process, and improve the model-solving speed.

Firstly, the variables $i_{jk}(t)$ and $u_{jk}(t)$, introduced to linearize the model, described as:

$$\begin{cases} i_{jk}(t) = I_{jk}^2(t) \\ u_k(t) = U_k^2(t) \end{cases}. \quad (27)$$

Then part of the constraint conditions change to:

$$P_k^{\text{PV}}(t) - P_k^L(t) = \sum_{l \in L(k)} P_{kl}(t) - \sum_{j \in J(k)} (P_{jk}(t) - r_{jk} i_{jk}(t)), \quad (28)$$

$$Q_k^{\text{inv}}(t) - Q_k^L(t) = \sum_{l \in L(k)} Q_{kl}(t) - \sum_{j \in J(k)} (Q_{jk}(t) - x_{jk} i_{jk}(t)), \quad (29)$$

$$u_k(t) = v_{j,k}(t) - 2(r_{jk} P_{jk}(t) + x_{jk} Q_{jk}(t)) + (r_{jk}^2 + x_{jk}^2) i_{jk}(t), \quad (30)$$

$$U_{\min}^2 \leq u_k(t) \leq U_{\max}^2, \forall k, t, \quad (31)$$

$$0 \leq i_{jk}(t) \leq (I_{jk}^{\max})^2. \quad (32)$$

Since the equation (20) is non-convex, it can be further processed by second-order cone relaxation, as:

$$\left\| \begin{matrix} 2P_{jk}(t) \\ 2Q_{jk}(t) \\ i_{jk}(t) - u_j(t) \end{matrix} \right\|_2 \leq i_{jk}(t) + u_j(t). \quad (33)$$

Meanwhile, the active power loss of distribution network is expressed as:

$$P_{\text{net,loss}} = \sum_{j,k \in B} r_{jk} i_{jk}(t). \quad (34)$$

The original nonlinear non-convex model for reactive power optimization considering the reliability of photovoltaic power supply has been transformed into an SOCP model, which can be quickly solved by tools such as Cplex and Gurobi.

4 Example analysis

4.1 Construction of typical distribution scenarios

Analysis of an IEEE 33-node distribution network example, connecting distributed photovoltaic power sources to nodes 6, 8, 10, 13, 15, 17, 21, 22, 25, 28, 31 and 33, respectively, in Figure 2. Each insert point is linked together with a photovoltaic power cluster with a capacity of 500 kW (10 kW $\times$ 50). The capacity of a solar inverter is 1.1 times that of the photovoltaic system. The line parameters of the system are detailed in [32].

Taking the mission profile of low latitude area in Malaysia as an example and considering that the spatial location of the distribution network is relatively concentrated, it is assumed that the ambient temperature and irradiance of each node in the distribution network area are consistent. According to the active and reactive load data of each node in the distribution system, the daily load data information of each node in the system is generated according to the typical daily load information of the IEEE-RTS system. The annual load data of the system is generated based on the Gaussian distribution. The IGBT module in the photovoltaic inverter is selected as FS25R12 W1T4_B11 IGBT module from Infineon.

In the arithmetic analysis, the focus is on the results of the IGBT reactive power optimization operation of photovoltaic-powered electrical equipment, and the comparative analysis between the traditional reactive power optimization strategy and the reactive power optimization strategy proposed in this paper. Firstly, the operation results of the distribution network were analyzed. After gaining the optimal active and reactive output of every distributed photovoltaic power source, the lifetime and dependability of IGBTs in the photovoltaic power supply are analyzed and the benefits of the strategy proposed in this text in achieving reactive power optimization and improving the reliability and lifetime of IGBTs are highlighted.

4.2 Analysis of distribution network operation results

Using the traditional reactive power optimization model with the objective of minimizing the distribution network losses and active reduction of photovoltaic power sources and the reactive power optimization model proposed in this paper considering the reliability of photovoltaic power sources for reactive power optimization, respectively, the comparison of distributed output apparent power of photovoltaic power sources at the distribution network node 6 is shown in Figure 3. Obviously, the proposed strategy leads

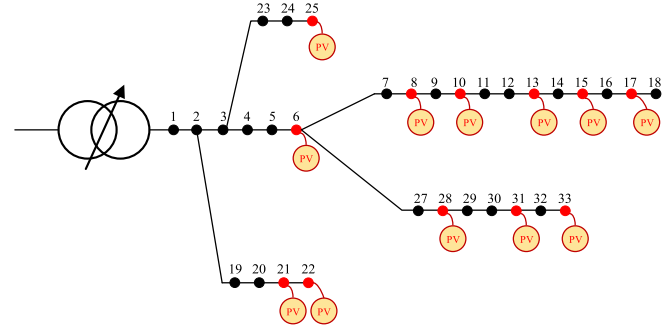


Fig. 2. IEEE 33-node distribution system.

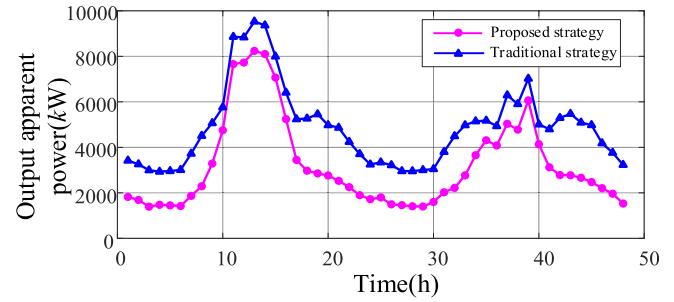


Fig. 3. Distributed photovoltaic power output apparent power (node 6).

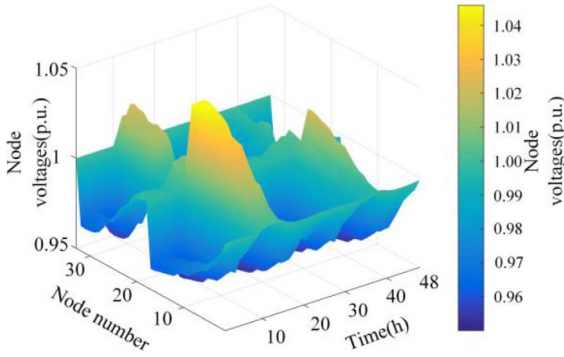
to a significant reduction in the apparent power output of the photovoltaic power supply as compared to traditional strategy. The reduction in the output current of the photovoltaic inverter, which in turn reduces the IGBT junction temperature, thus contributes to the reliability of the photovoltaic inverter.

Under the three strategies of no strategy, the traditional strategy and the proposed strategy, the corresponding distribution network line loss, active power reduction of photovoltaic power generation and total loss are shown in Table 1. Under the proposed strategy, the distribution network operational active losses, photovoltaic generation active reduction, and total losses are lower than the no strategy and slightly higher than the traditional strategy. In the proposed strategy, the reactive power output capability of inverters is limited, so the total distribution losses are slightly higher than the total distribution losses under the traditional strategy. Overall, the proposed strategy can balance the improvement of the operating dependability of the distribution grid's photovoltaic inverters with the reduction of the total losses in the distribution network.

The voltage distribution at each node of the IEEE 33-node distribution system under the proposed strategy with a voltage reference of 12.66 kV is shown in Figure 4. The voltage of each node of the distribution network is in the range of 0.95–1.05. It can be seen that the proposed approach complies with the requirements for the safe and stable functioning of the distribution grid voltage and ensures that the voltage at each node of the network is not exceeded.

Table 1. Distribution network losses under three strategies.

Distribution network operation mode	Line losses/MWh	Photovoltaic active power reduction/MWh	Total loss /MWh
No strategy	931.58	0	931.58
Traditional strategy	545.08	3.77	548.85
Proposed strategy	614.18	5.67	619.85

**Fig. 4.** Voltage at each node of the distribution grid.

4.3 IGBT lifetime and reliability analysis

After obtaining the operating results of each distributed power source in the distribution grid, the IGBT reliability and lifetime are further analyzed on this basis. The IGBT junction temperature directly affects the lifetime and reliability of the IGBT, which in turn affects the operational reliability of the photovoltaic inverters and the active distribution grid. To achieve coordination and unity between the reactive power optimization of the distribution grid and the reliability and operational lifetime of the photovoltaic inverter, the maximum junction temperature of the IGBTs is integrated into the target of the reactive power optimization of the active distribution power grid in this paper. In the distribution grid, there are multiple distributed photovoltaic access nodes. To facilitate the illustration, node 6 and node 25, which exhibit higher junction temperatures under the traditional strategy, are taken as examples for comparing and analyzing the junction temperatures of the IGBTs under the traditional strategy and the proposed strategy, as depicted in Figure 5. At both node 6 and node 25, the junction temperature of the IGBTs under the traditional strategy is much higher than that of the IGBTs under the proposed strategy. It can be seen that the proposed strategy can realize an effective reduction of the junction temperature of the IGBTs with higher junction temperature, which improves the overall reliability of the photovoltaic inverters in the distribution network.

The distributed IGBTs junction temperature data at node 6 and node 25 locations are calculated to obtain the heat load information, as shown in Figure 6. At node 6, the number of IGBT average junction temperature concentrated at 40–50 °C decreased significantly, and the number of IGBT junction temperature fluctuation concentrated at

40–50 °C decreased significantly. At node 25, the statistics of the average IGBT junction temperature concentrated at 40–50 °C decreased significantly, and the statistics of the junction temperature fluctuation concentrated at 40–50 °C decreased significantly. As can be seen, the proposed strategy causes the junction temperature of the IGBTs to be relatively concentrated in areas with lower junction temperature mean and fluctuation. Reducing the mean junction temperature and junction temperature fluctuation can effectively improve the operational reliability and lifetime of IGBT. So the proposed method has the effect of extending the lifetime and reliability of the IGBTs.

The results of the reliability study of the IGBTs at nodes 6 and 25 in the IEEE 33-node distribution system under the traditional and proposed strategies are shown in Figure 7, by the photovoltaic inverter reliability evaluation method based on the mission profile. The IGBTs replacement cycle is generally 20–30 years at the moment of photovoltaic power plant planning and design, this paper takes the IGBT replacement time of 20 years as an example. The lower the failure rate corresponding to the IGBT operation time of 20 years, the more reliable the photovoltaic inverter operation is. At the same time, the IGBT operation time corresponding to 10% failure rate is taken as the reliable operation lifetime of the IGBTs, namely, the confidence level of no failure of IGBT within the reliable operation lifetime is 90%. It can be seen that under the proposed strategy, the reliability of IGBT running for 20 years has been significantly improved at node 6 and node 25.

The failure rates of photovoltaic inverters at each access point in the IEEE 33-node distribution system operating for 20 years are shown in Figure 8. It is clear that under the proposed strategy, the photovoltaic inverter fault region is significantly reduced, and the IGBT fault rate is significantly reduced at most of the access points in the distribution network. Under the traditional strategy, the maximum and average failure rates of IGBTs in all access points are 1 and 0.7023, respectively; under the proposed strategy, the maximum and average failure rates of IGBTs in all access points are 0.5299 and 0.4000, respectively. The maximum and average failure rates of IGBTs in all access points are significantly reduced, which verifies the effectiveness of the proposed strategy in enhancing the power supply reliability of distributed photovoltaic power sources in photovoltaic high-penetration active distribution power grid.

The lifetime estimation results of IGBTs accessed at distribution nodes 6, 8, 10, 13, 15, 17, 21, 22, 25, 28, 31 and 33 are shown in Table 2. Under the traditional strategy, the minimum and average lifetimes of the IGBTs in all access points are 1 year and 8 years, respectively; under the

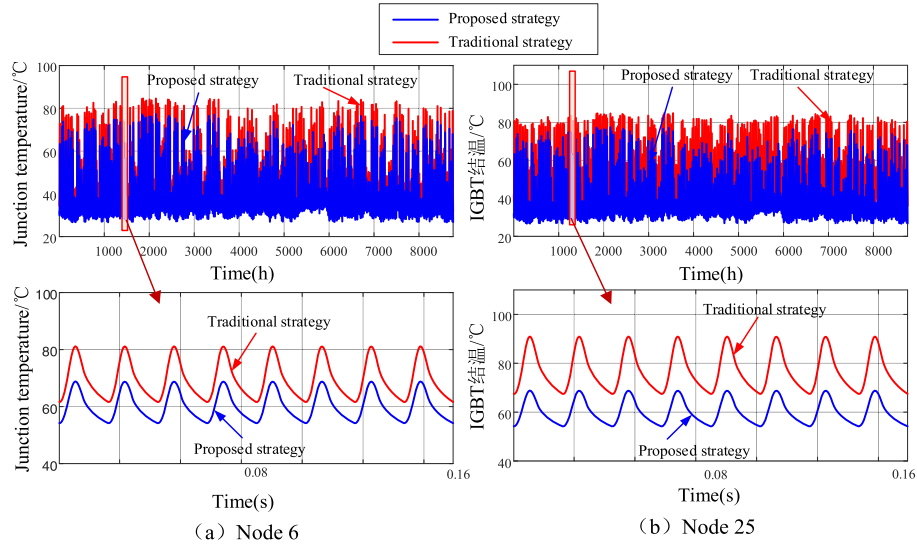


Fig. 5. IGBT junction temperature of photovoltaic inverter.

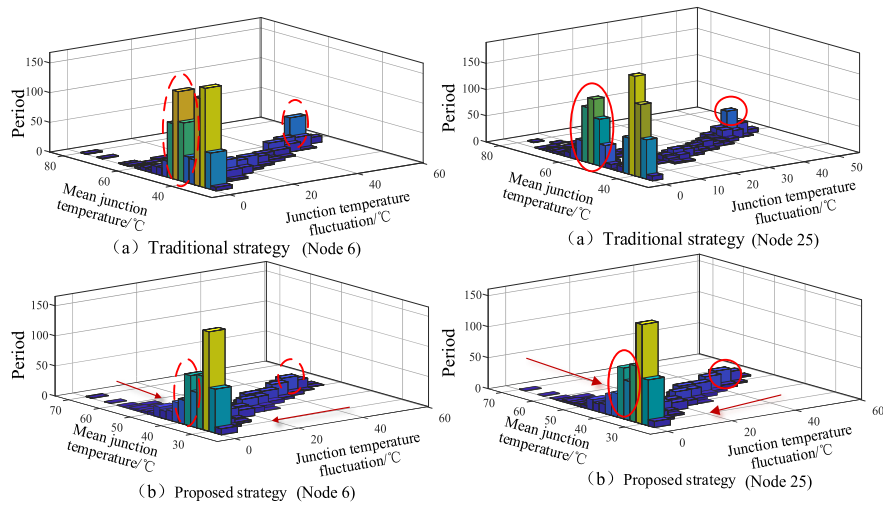


Fig. 6. Statistics of IGBT thermal load information of photovoltaic inverter.

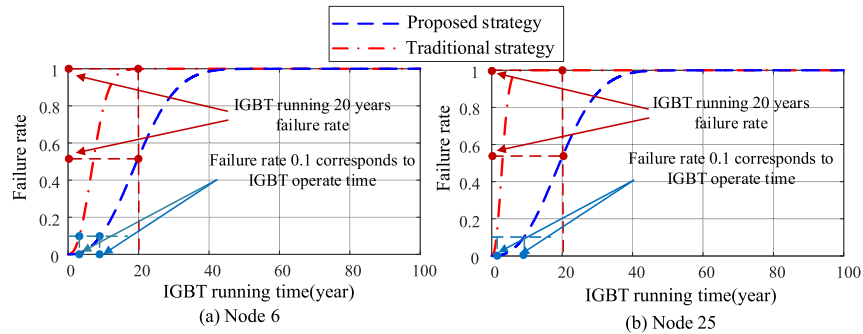


Fig. 7. Statistics of IGBT thermal load information of photovoltaic inverter.

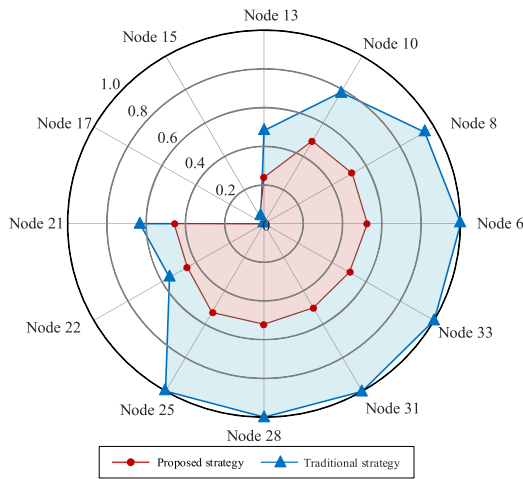


Fig. 8. Statistics of IGBT thermal load information of photovoltaic inverter.

Table 2. IGBT lifetime under two strategies.

Node	IGBT lifetime under traditional strategy (year)	IGBT lifetime under proposed strategy (year)	Effect (year)
6	4	10	+6
8	6	10	+4
10	7	10	+3
13	10	14	+4
15	20	20	0
17	20	20	0
21	8	11	+3
22	9	10	+1
25	2	9	+7
28	2	10	+8
31	1	10	+9
33	4	10	+6

proposed strategy, the minimum and average lifetimes of the IGBTs in all access points are 9 years and 12 years, respectively. Under the strategy proposed in this paper, the average junction temperature and junction temperature fluctuation of IGBT are effectively reduced, and the minimum lifetime and average lifetime of all IGBTs are increased by 8 years and 4 years respectively. According to the results, the implementation of the proposed strategy demonstrates a substantial enhancement in the lifespan of the IGBTs, while also optimizing reactive power in the distribution grid and extending the reliable operation time of the IGBTs in the power supply.

The IGBT lifetime of photovoltaic inverter at each access point under the two strategies is shown in Figure 9. It is clear that the overall effective area of photovoltaic inverter at all access points under the proposed strategy is larger than that of the traditional strategy, indicating that the overall lifetime performance of all photovoltaic inverter

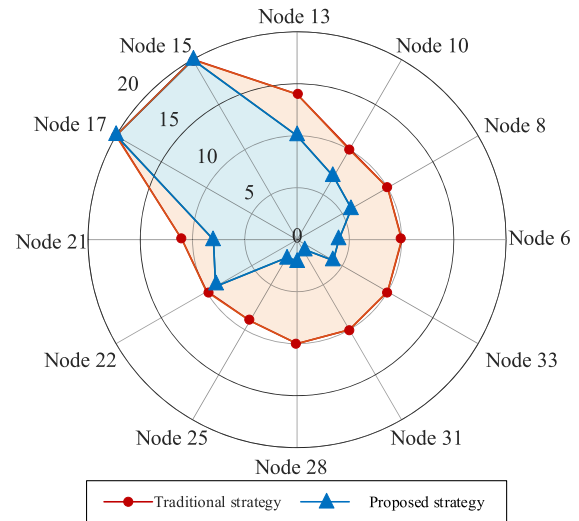


Fig. 9. Photovoltaic inverter IGBT lifetime at each access point.

in the distribution network area is significantly improved under the proposed strategy. Under comprehensive consideration, the strategy proposed in this paper can improve the overall reliability when a high proportion of distributed photovoltaic participates in the voltage/reactive control of the distribution network.

Conclusion

1. A quantitative assessment of IGBT dependability considering photovoltaic reactive output was completed based on the target scenario;
2. The maximum junction temperature indicator of IGBT was introduced into the objective function of voltage/reactive optimization of the distribution network, and an improved multi-objective voltage/reactive optimization model for active distribution network is constructed, which realizes the thermal management of the junction temperature of the IGBT and photovoltaic participation in the optimal regulation of the voltage/reactive of the active distribution network;
3. In an IEEE 33-nodes distribution system, the minimum and average life expectancies of IGBT at all access points are improved by 8 and 4 years, respectively, which in a large sense prolongs the operating life expectancy and dependability of photovoltaic inverters.

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Conflict of interest

The authors declare no conflict of interest.

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