

IEEE Recommended Practice for Use of an Unmanned Aerial Vehicle for Substation Inspection

IEEE SA Board of Governors

Developed by the
Entity Collaborative Activities Governance Board

IEEE Std 3327™-2025

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Entity Collaborative Activities Governance Board
of the
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Approved 12 February 2025

IEEE SA Standards Board

Abstract: Described in this document is the recommended use method of unmanned aerial vehicle (UAV) for substation inspection. The composition and technical conditions of a UAV inspection system, inspection objects and methods, inspection operation methods, inspection data processing, and UAV maintenance are introduced. This method is applicable to the use of UAVs that inspect and test substation equipment and the surrounding environment.

Keywords: data processing, IEEE 3327, inspection content, inspection operation methods, substation inspection, technical conditions, UAV inspection system

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

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PDF: ISBN 979-8-8557-1926-0 STD27751
Print: ISBN 979-8-8557-1927-7 STDPD27751

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Participants

At the time this IEEE recommended practice was completed, the Substation Inspection-Unmanned Aerial Vehicle Working Group had the following membership:

Huanqing Cai, *Chair*
Guifeng Zhang, *Vice Chair*
Junjie Xiong, *Secretary*

Organization

China Automotive Engineering Research Institute
China Southern Power Grid Co., Ltd.
Hangzhou Shenhao Technology Co., Ltd.
Shandong Electrical Engineering & Equipment Group Co., Ltd.
Southeast University
State Grid Corporation of China
Tsinghua University
Xian Jiaotong University

Name of Designated Representative

Benwang Li
Guifeng Zhang
Junjie Xiong
Hongtai He
Aiguo Song
Huanqing Cai
Bin Wang
Hui Cao

The Working Group gratefully acknowledges the contributions of the following participants:

Bojian Chen
Guokun Chen
Jian Ding
Jianhui Feng
Jing Fu
Kegui Guo
Zhiguang Guo
Tengfei Han
Yingzhuo Huang
Qinjie Ji
Bo Li
Fan Li
Hao Li
Peng Li
Wei Li
You Li

Jianquan Liang
Heqian Liu
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Deborah R. Hagar	Hiroshi Mano	Sha Wei
Guido R. Hiertz		Luyang (Eric) Zhang

Introduction

This introduction is not part of IEEE Std 3327-2025, IEEE Recommended Practice for Use of an Unmanned Aerial Vehicle for Substation Inspection.

In the operation and maintenance of substation equipment, it is very important to improve the observability of equipment status. The substation equipment is arranged in layers, with wide inspection areas and many points, and the ground inspection perspective is limited, but the problem of inadequate middle- and high-rise equipment inspection can be solved through unmanned aerial vehicle (UAV) inspection. Using a UAV to carry out multi-perspective and close inspection and detection of equipment has been widely used, and a three-dimensional inspection mode is formed with manual inspection of substations, robot inspection, and an online monitoring system. This document provides recommended uses of the UAV for substation inspection as a guide for its effective implementation in substation operation and maintenance (O&M).

This recommended practice first introduces the composition and technical conditions of a UAV inspection system for substations. It clarifies the application scenarios, objects, and methods of UAV inspection and recommends the inspection operational methods, data processing analysis, and inspection system management. The patrol inspection operation process is provided as the guidance for field application. In Annex A, with a 500 kV substation as the application scenario, a complete process of substation application, inspection, and detection is given.

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IEEE Recommended Practice for Use of an Unmanned Aerial Vehicle for Substation Inspection

1. Overview

1.1 Scope

This recommended practice describes the use of an unmanned aerial vehicle (UAV) in electrical substation inspection. The composition of a UAV inspection system, technical conditions, operator recommendations, operating environment recommendations, applicable inspection scenarios, inspection characteristics, data processing, and UAV maintenance are described. This document applies to the use of UAVs in intelligent inspection and live detection of substation equipment and the surrounding environment.

1.2 Purpose

The purpose of this recommended practice is to:

- Formulate the general and technical application specifications for UAVs in substation inspection
- Unify technical conditions, personnel requirements, and operating environment requirements during the process of substation inspection
- Define typical scenarios of inspection
- Define the process of inspection and its data processing

The operation and maintenance personnel can use UAVs to conduct inspections more safely, reliably, and efficiently under the guidance of this recommended practice. It also helps promote the application and development of UAVs in substation inspection worldwide, improves the efficiency and quality of substation inspection comprehensively, helps prevent risk to operations and maintenance personnel from ascending operations, and increases the safety and reliability of the power grid.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{6,7}

⁶ The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

⁷ The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEEE Std 1936.1™-2021, IEEE Standard for Drone Applications Framework.

IEEE Std 2821™-2020, IEEE Guide for Unmanned Aerial Vehicle-Based Patrol Inspection System for Transmission Lines.^{8, 9}

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.¹⁰

inspection operated or controlled automatically: According to the preset inspection route, the automatic control of the unmanned aerial vehicle (UAV) to the designated position and the automatic collection of inspection data.

inspection operated or controlled by hand: The operator controls the unmanned aerial vehicle (UAV) takeoff, data collection mode reaching the designated location, and landing.

inspection route: The inspection path formed by a series of two or more inspection points connected in a certain order.

inspection way points: The unmanned aerial vehicle (UAV) inspection position point is composed of longitude, latitude, absolute elevation, and other position information and mission load parameter information.

unmanned aerial vehicle (UAV) docking station: Comprises the main control module, electrical module, communication module, monitoring module, take-off and landing platform, and more, and is equipped with the functions of substation UAV inspection task distribution, UAV control, operation monitoring, data forwarding, UAV recovery, and so on.

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⁹ IEEE publications are available from The Institute of Electrical and Electronics Engineers (<https://standards.ieee.org/>).

¹⁰ *IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

unmanned aerial vehicle (UAV) inspection for substation: The process of data collection, processing, and analysis of the substation equipment and surrounding environment with visible light camera, infrared thermal imager, and other task loads.

unmanned aerial vehicle (UAV) inspection system for substation: A work device that uses UAV as flight platforms and carries mission payloads to patrol and detection equipment, facilities, and surrounding environments of a substation. It consists of UAV, mission payloads, UAV docking stations, data processing and analysis terminals, and UAV inspection auxiliary equipment.

3.2 Acronyms and abbreviations

3D LiDAR	three-dimensional light detection and ranging
DEM	digital elevation model
DOM	digital orthophoto map
GNSS	global navigation satellite system
IMU	inertial measurement unit
RTK	real-time kinematic
UAV	unmanned aerial vehicle

4. The composition of a UAV inspection system and technical conditions

4.1 System composition

The UAV inspection system of the substation is mainly composed of a UAV, UAV docking station, task load, and UAV inspection auxiliary equipment, which is an integrated software and hardware system used for inspection and testing of outdoor equipment and facilities and the surrounding environment of the substation. In addition, intelligent processing and analysis technology is gradually applied to UAV inspection operations, and data processing and analysis terminals are also recommended to reduce the workload of manual interpretation.

See Figure 1 for the composition diagram of a UAV inspection system, which is introduced as follows:

- a) The UAV is used to carry the mission load to conduct flight inspection of the substation, mainly composed of the UAV body, communication control module, power module, etc. An electric multi-rotor UAV should be used for substation inspection.
- b) The UAV docking station is used to charge or change the UAV's power battery, control the UAV's takeoff, inspection tasks, and landing, as well as recycle and store the UAV. To support the autonomous inspection of the substation, it is suggested to deploy the UAV docking station in the substation. If no UAV docking station is deployed, the remote control and control screen can be used to control the UAV to carry out the substation inspection operation.
- c) Task load is used for the collection, recording, and processing of inspection data, mainly including visible light load, infrared load, and three-dimensional light detection and ranging (3D LiDAR) scanning load.
- d) The data processing and analysis terminal is used to process and analyze inspection data such as visual images, infrared images, and laser point cloud, and to generate the required inspection results.

- e) UAV inspection auxiliary equipment is used to support the development of UAV operation, maintenance of the UAV inspection system, etc. It mainly includes equipment and facilities for flight, safety, and maintenance assistance. It may include a telescope, backup power supply, and anemometer. According to the field environmental conditions, standby apron, fire extinguisher, battery explosion-proof box, warning belt, anti-static gloves, and other safety facilities and appliances should be configured. Battery charging equipment, battery voltage detector, and maintenance instruments should be configured and equipped with sufficient spare parts to meet the daily maintenance requirements. The UAV warehouse should be equipped with functions of entry and exit management and intelligent management of battery charging and discharging.

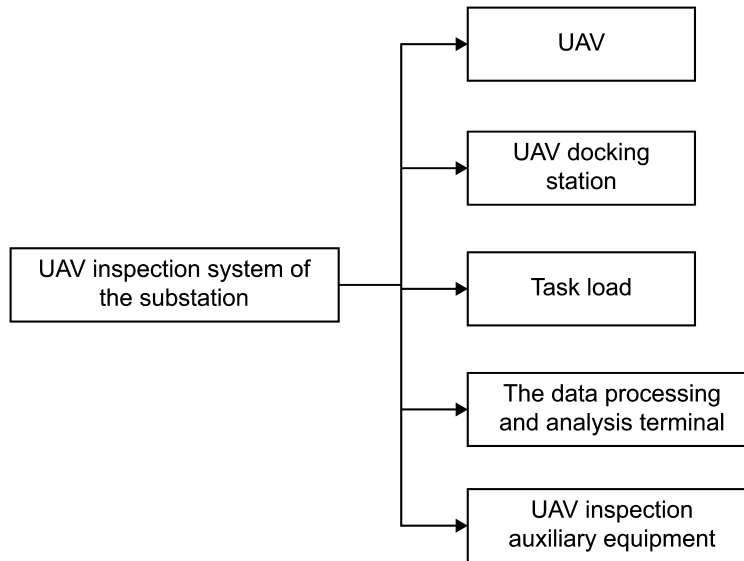


Figure 1 —Composition diagram of UAV inspection system in a substation

4.2 Technical recommendations

4.2.1 Appearance and structure

4.2.1.1 Appearance and structure of the UAV

According to the characteristics of dense equipment and compact layout, the structure and size of a UAV for substation inspection are recommended as follows:

- The surface of the UAV should be intact, the structural parts should be firmly connected, and the power connector should be of an anti-ignition design.
- The fuselage, frame, and blade should use insulated materials.
- There should be obvious signs on the rotor indicating the installation direction.
- The fuselage should have navigation lights to visually indicate the working status of the UAV.
- In order to meet the requirements of safe distance of UAV inspection between substation equipment, it is recommended to use a small UAV. The axial distance of the UAV should not be greater than 1000 mm.

4.2.1.2 UAV docking station appearance and structure

If the UAV docking station is deployed in the substation, the recommended appearance and structure of the UAV docking station is as follows:

- The docking station structure is stable, the surface is uniform, and there are no bubbles, cracking, or shedding defects.
- The docking station logo should be clear and easy to identify. Internal electrical lines should use eye-catching colors and graphics for clarity.
- All connections and fasteners should have anti-loosening measures, and the removable parts should not be installed with temporary measures such as glue and tape.
- The docking station with a UAV storage function should be equipped with an emergency stop function button for emergencies.
- The size and weight of the docking station should follow the substation's site requirements.
- The docking station's hatch should have a remote or local switch function. While operating the hatch door, confirm that the motor works normally, the limit switch works normally, and that the door has no deformations, smooth and fluent movement, no blocking, no jamming, no flaking or missing paint, no corrosion, and no abnormal sounds.
- The docking station should have the function of positioning the UAV. The return device should have no deformation, smooth and fluent movement without blocking or jamming, and no abnormal sounds.

4.2.2 Functional configurations

4.2.2.1 UAV flight safety strategy

It is necessary to develop a UAV flight safety strategy to safely and reliably carry out UAV inspection operations. Suggested flight security functions include self-check, automatic obstacle avoidance, communication interruption protection, low power control protection, flight area limit, autopiloted one-key return, and emergency control. The recommended function configuration is as follows:

- Self-checking. The stability of the UAV inspection system may be affected by the failure and mechanical damage of the electronic components. The UAV should have the function of startup self-inspection, including at least the self-inspection of battery power, network communication and navigation status, and alarm with obvious sound (or light) signal or other ways, and can quickly locate the fault according to the alarm prompt. The UAV docking station should have the function of startup self-inspection, including at least the self-inspection of the UAV docking station operation state, mechanical control state, environmental information, and network communication. If any self-inspection item does not meet the requirements, the alarm should be given with an eye-catching icon, and the operation should not be carried out.
- Automatic obstacle avoidance. UAVs need to be maneuverable in complex working environments and among compact substation equipment. Therefore, the UAV should be able to perceive and avoid obstacles in six directions (including forward, backward, left, right, up, and down), decelerate, hover, and actively maneuver around obstacles during the flight mission.
- Communication interrupt protection. UAV communication can be vulnerable to substation electromagnetic environment interference, so to help ensure the safety of operation, UAVs should have a communication interrupt protection flight platform, communication interruption in the mission, and should be able to hover in the preset communication signal recovery waiting time if the waiting time communication signal recovery can continue to perform the task. It should also be capable of autonomous return.
- Low power runaway protection. The UAV should have the function of low power out of control protection. If necessary, the UAV can return autonomously or land in a safe area.
- Flight area restriction. To avoid entering the no-fly area, the UAV should have the function of limiting the flight area, and the flight limit area should be set freely. If the takeoff point is located in the no-fly area and the UAV is hovering, the UAV should hover and wait or interrupt the flight task if necessary.

- One-key autopiloted return flight. One-click return flight is a measure under emergency conditions to avoid possible damage to the UAV. The UAV should have a one-button return function. For example, when the UAV loses communication with the ground control station, the UAV should be able to determine that it is in a state of disconnection and automatically make a decision to return. After the return function is activated at any time in the flight mission, the UAV should immediately terminate the current mission and return home. The return strategy (route, speed, etc.) should be set in advance.
- Emergency control function. When the UAV deviates from the preset route due to factors like abnormal weather, strong electromagnetic interference, or other emergency situations, an emergency control function can be activated.

4.2.2.2 Task support functions

To improve the work efficiency of substation UAV inspection and help the efficient execution of inspection tasks, the task support functions include flight mode switching, route planning, breakpoint continuation, and remote real-time flight control functions. The recommended function configurations are as follows:

- Flight mode switching. It is appropriate to have the function of flight mode switching, and it should have both manual and autonomous flight modes, and they can be switched to each other. The flight state should be kept stable during the switching process.
- Route planning. Moreover, it is advisable to have a route planning function, which can set the take-off and landing mode, flight speed, and navigation point information.
- Breakpoint continued flight. When the autonomous inspection task is interrupted and the UAV returns to carry out the autonomous inspection task again, in order to help ensure the inspection efficiency, the inspection task should not be started from scratch. The UAV should have the function of breakpoint continuous flight, which can record the breakpoint information in the flight mission, relocate to the breakpoint position after resuming the flight, and continue to perform the flight mission.
- In order to meet the requirements of substation emergency and temporary inspection tasks, it is suggested to support the remote real-time flight control function.

4.2.2.3 Task load function

The UAV load function should meet the following guidelines:

- a) For the visible light task equipment:
 - 1) In order to enable the UAV to take clear photos or videos at a distance of not less than 3 m from the inspection targets of the substation, and to clearly distinguish bolts and nuts (i.e., millimeter-level inspection targets) in the photos or videos taken, it is recommended that the optical zoom ratio of the visible light camera be no less than five times, and the resolution be no less than (3840×2160) DPI.
 - 2) To meet the shooting needs in the process of UAV movement, it is appropriate to have the function of fast automatic focus.
 - 3) To help ensure the inspection operation of multiple directions on the substation, it is recommended that the cradle pitch angle of visible camera is -90° to 30° (30° is to help ensure that the bottom of electrical equipment in the middle and high level of the substation is photographed completely) and the horizontal rotation angle is -90° to 90° . To help ensure the imaging effect, the cradle with small jitter angle should be given priority.
- b) For infrared task equipment:
 - 1) The resolution of the infrared map should not be lower than (640×480) DPI.