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VOLTAGE MASTERY: TACKLING URBAN CHALLENGES THROUGH EFFICIENT POWER CONTROL IN HIGH-VOLTAGE GRIDS

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Abstract

Ensuring the security and reliability of power supply stands as a pivotal necessity in today's modern society, impacting a wide array of critical sectors, including telecommunications, finance, water supply, healthcare, and manufacturing. The effective safety warning mechanism, with its capacity for sensitive and precise hazard forecasting and timely dissemination of warnings, plays an indispensable role in averting disasters and mitigating the resultant harm to life and property. In recent years, extensive efforts have been dedicated to comprehending the behavior of power systems during large-scale blackouts, necessitating simulations to study the impact of diverse factors. Concurrently, the demand for grid risk early warning methods has surged in the realm of power emergency management.

This paper seeks to provide a holistic perspective on the subject by delineating three crucial dimensions of the smart grid security defense system.

1. Introduction

The security and reliability of power supply is crucial for various aspects of modern society, including telecommunications, finance, water supply, hospitals, and manufacturing. The safety warning mechanism refers to the sensitive and accurate release of hazard omens and the provision of timely warnings to take appropriate measures. Its role is to provide advance feedback and make timely arrangements to prevent future accidents and minimize the damage to life and property caused by accidents. [1]

In recent years, to understand the characteristics and laws of power systems under the influence of different factors in the occurrence of large area blackouts better, experts have been conducting simulations of power system large area blackout accidents. In view of the substantial requirements of power emergency management for grid risk early warning, the research of grid risk early warning methods has gradually received attention. [2]In view of the substantial requirements of power emergency management for grid risk early warning, the research of grid risk early warning methods has gradually received attention.[3]

This article presents three dimensions of the smart grid security defence system to provide a comprehensive understanding of the topic.

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Security technology dimension. The security technology dimension is the technical support of the smart grid security defence system, which is mainly a dimension based on the OSI network model. The five types of security services can comprehensively reflect all the functions and contents of the security defence system, enabling the positioning of potential security threats in the grid information system and the formulation of reasonable security measures.[4] In the security technology dimension, the five types of security services are the security measures that can locate security threats in the system, while the eight security mechanisms are the technical means to implement the five types of security services.

Security policy dimension. The security policy dimension is the most critical dimension of the smart grid security defence system, mainly including six links: warning, protection, detection, response, recovery and counter-attack. These six aspects are not simply circular, but have a certain dynamic, sequential and continuous nature. In the construction of an active three-dimensional defence system for smart grids, the security policy dimension plays a very important role and the dynamic continuity of the six links is more in line with the actual network situation.[6] In the smart grid network environment, information security is dynamic and variable, and is gradually being improved as technology evolves.

Safety and security dimension. Safety assurance dimension is a scientific and effective method to manage and regulate personnel and their operation behaviour, thus providing security for the system safety of smart grid.[7] This includes the following five aspects of security: system security, personnel security, training security, audit security and management platform security. It plays an important role in the operation of the entire grid, providing a strong guarantee for the normal operation of each link, module and security phase.

Overall, this article highlights the importance of grid risk early warning methods in ensuring the security and reliability of power supply. By implementing the three dimensions of the smart grid security defence system, power grids can effectively identify potential threats and implement appropriate security measures to prevent accidents and minimize damage to life and property. [8]

2. Model Building

2.1. Grid Structure

2.1.1. System Structure

Most of the grids studied at home and abroad are AC networks, often connected to the grid through power electronic conversion devices, whose power output characteristics, depend largely on their component types, organizational structure and control strategies. The control requirements are high for each distributed power source [9], so the control scheme may not be well optimized and applicable to the grid, and multiple inverters are required. Additionally, the use of multiple inverters can increase system costs and complexity, resulting in significant power electronics waste [10] to address this issue, this paper aims to build on existing technology and develop a grid system that can be used for high-quality power distribution applications to ensure grid reliability and quality. However, current research has been primarily focused on individual aspects of the grid without analysing and studying the entire system's operation. Therefore, there is an urgent need for comprehensive research in this area [11].

The grid studied in this paper consists of two layers: the physical layer and the network layer. The physical layer comprises three buses: the positive line (P line), the neutral line (O line), and the negative line (N line). In addition to the distributed power supply (DG), the converter (DC-DC), and the low-voltage load, as shown in Figure 1. The distributed power supply (DG) is connected to the bus through the DC-DC converter, and the distributed power supply DG and converter DC-DC reduce the coupling between the system and make the system easier to expand on the basis of the traditional voltage stabilization function, and also suppress the power fluctuation caused by the unbalance of power supply and load, and weaken the impact of different disturbances on the system voltage quality, so that the system has higher The system has higher energy efficiency and lower operating cost. Low voltage loads are connected between PO (positive and neutral) or NO (negative and neutral). And the network layer helps multiple DC-DC converters to interact with information, which can keep a large amount of information in a small parameter space in the consistent control of voltage imbalance. The DC-DC converters corresponding to positive and negative poles are considered as the same node, while they are treated as different nodes in bus average voltage control. The nodes are connected through a sporadic communication network, and different nodes are assigned to handle different computation and communication tasks. By exchanging information of control variables with neighbouring nodes to update their control information, they achieve global consistency of control variables [12].

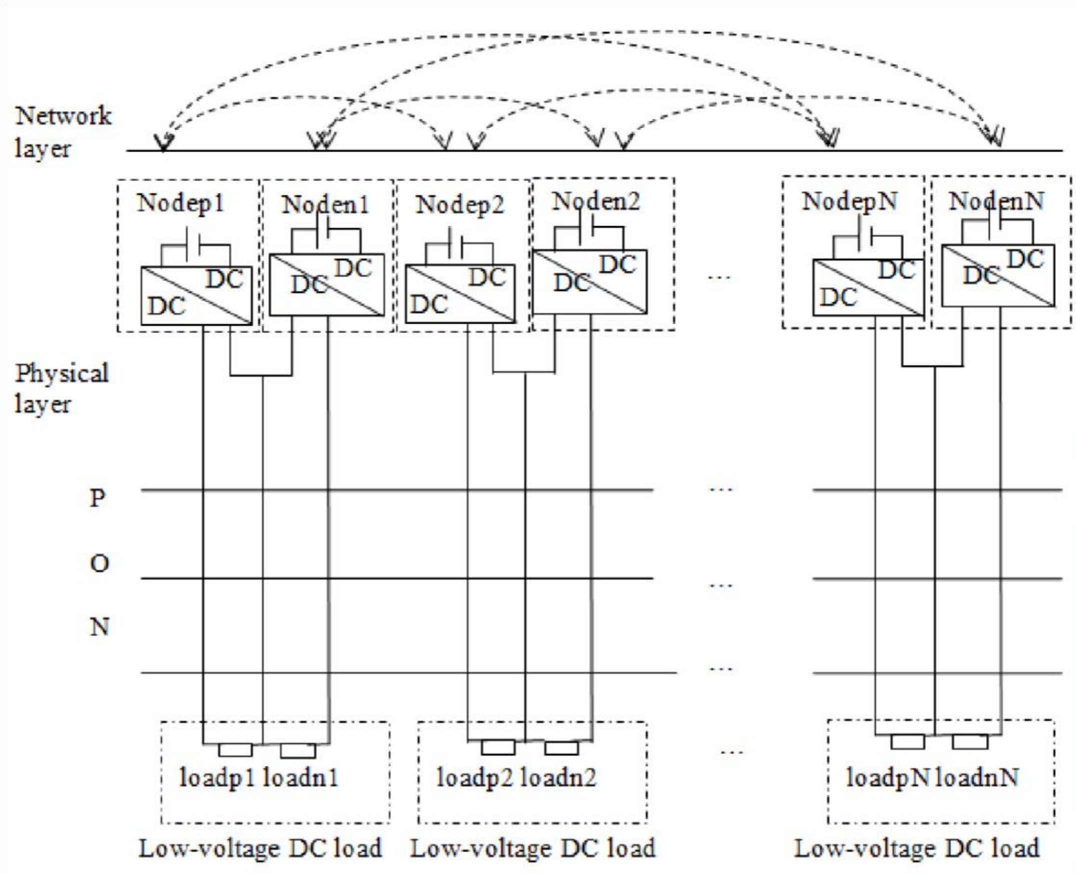
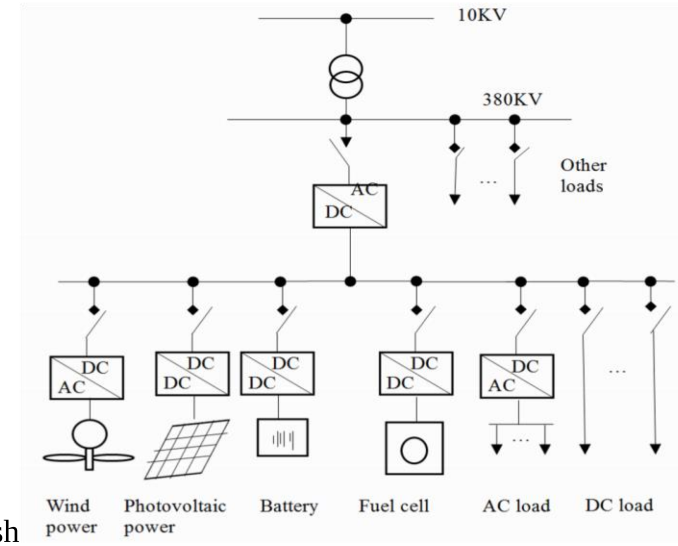


Figure 1: Schematic diagram of the power grid structure.

2.1.2. Topology

The power network that realizes the connection and control of power sources, energy storage devices, and loads through electronics can be considered as a complex network composed of different energy flows to meet different terminal demands, i.e., a multi-source, multi-sink, multi-path energy flow network. When the system structure changes, it needs to be recalculated, so the grid uses decentralized control methods to achieve free connection or disconnection of generators and loads, grid-connected operation, independent operation, and improved power utilization efficiency, which is an ideal control



method with the topology shown in Figure 2.

Figure 2: Typical topology of the power grid.

5

Table 1 lists the interfaces of common power sources and energy storage devices, with wind power and micro-gas generators outputting AC power and other power sources and energy storage devices outputting DC power. The structure of the former is relatively fixed, while the structure of the latter allows for some flexibility. Since the inverter structure is more complex than the converter, the direct grid is more suitable as a grid structure for high-frequency AC power, AC power and energy storage devices compared to the AC grid, which can improve the performance of existing systems and reduce the usage of electronics while ensuring the efficiency of power utilization.

Table 1: Common power and energy storage device interfaces.

Power supply / Energy storage device	Output power	AC grid interface	Grid interface
Wind power	AC	Direct connection/rectifier-inverter	Rectifier
Photovoltaic power	DC	Inverter	Converter
Fuel cell	DC	Inverter	Converter
Micro gas turbine	AC	Rectifier-inverter	Rectifier
Battery	DC	Inverter	Converter
Supercapacitor	DC	Inverter	Converter
Superconducting energy storage	DC	Inverter	Converter

2.2. Interface and Controller

The output voltage of the power supply is generally low, but the perturbation in the output current and output voltage can have a significant impact. Therefore, a DC/DC converter is usually required to step up a stable voltage before connecting to the grid. When the energy storage device is connected to the grid, it needs the energy to be able to flow in both directions so that the output current and output voltage values tend to be stable. With bi-directional nature, so a one-way converter is not suitable Instead, converters that can allow energy to flow in both directions must be used, particularly for larger supply ranges and longer lines.

One such converter is the Boost converter, which offers high efficiency due to its free and flexible characteristics. It charges a set of capacitors through an external device and has a simple and intuitive structure and drive circuit consisting of a switching tube (S), a diode (B), a boost inductor (Lf) and a capacitor (Cf), as shown in Figure 3.

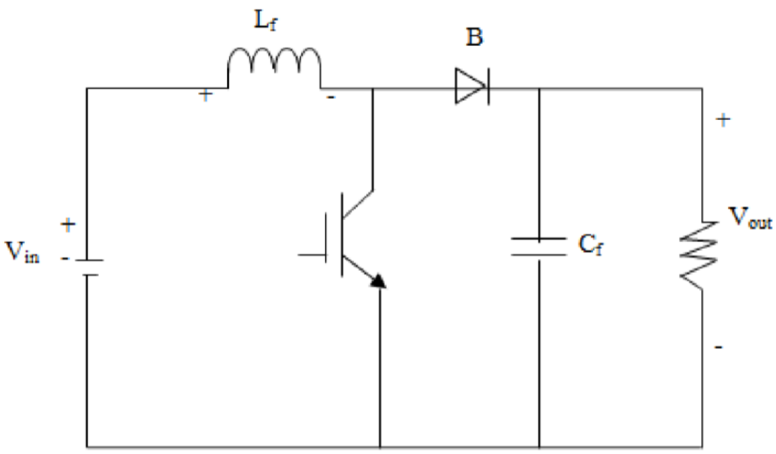


Figure 3: Typical topology of the power grid.

In continuous operation mode, the relationship between the output voltage Vout and the input voltage Vin of the Boost converter is as follows.

$$\frac{V_{out}}{V_{in}} = \frac{1}{1-D} \quad (1)$$

In Eq. 1, D is the duty cycle of S conduction in one switching cycle. In order to achieve a power supply that can be connected in parallel to the bus, it should be necessary to keep the voltage at its output stable for the purpose of equalizing the voltage, which is generally controlled by a double loop, i.e., voltage outer loop and current inner loop control. Therefore, the Boost converter uses the output voltage for control, i.e., the output voltage Vout is controlled to be a constant value.

The control principle of the Boost converter is shown in Figure 4. The control system collects the output side voltage Vout and compares it with the set voltage value Vref to obtain the deviation value ΔV. After the PI link, it compares it with the delta carrier signal to obtain the control amount of the switching element S. Finally, the control signals are generated by two double closed-loop control systems to realize the opening and closing of the supply parallel Boost converter switching tubes, so that the output current and output voltage values are stabilized and the duty cycle D is controlled.

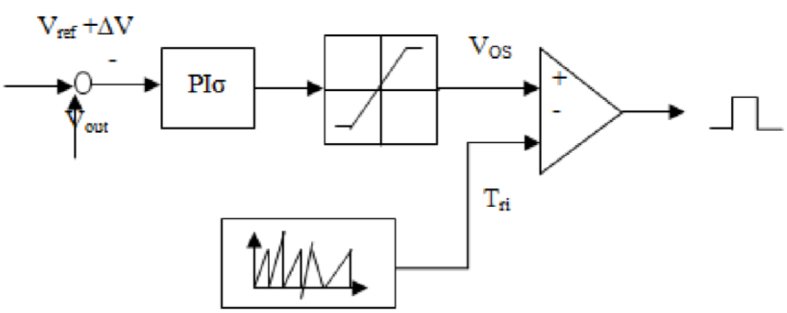


Figure 4: Typical topology of the power grid.

3. Model Experiment and Technical Summary

3.1. Model Experiment

In the design of the average voltage consistency control, the adjacency matrix with 0-1 weights equation 9 is used as:

$$A=\begin{bmatrix} 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \end{bmatrix} \quad (2)$$

Since the reference value of voltage unbalance is added to the control of unbalance consistency, the adjacency matrix of its 0-1 weights Equation 10 is:

$$A=\begin{bmatrix}0&1&0&0&0\\1&0&1&0&1\\0&1&0&1&0\\0&0&1&0&1\\0&1&0&1&0\end{bmatrix} \qquad (3)$$

At the initial moment, the loads of each node of the positive terminal are Rp1=10Ω, Rp2=20Ω, Rp3=20, Rp4=20Ω, and the loads of each node of the negative terminal are Rn1=20Ω, Rn2=40Ω, Rn3=20Ω, Rn4=5Ω, and the relevant parameters of the simulation model and the controller are shown in Table 2.

Table 2: Common power and energy storage device interfaces.

parameter	value	parameter	value
vref/V	400	kI	3
RLpi, RLni /Ω	0.03	kPhbi	10
Rmi/Ω	0.01	kIhbi	0.05
Rdpi,Rdni /Ω	0.02	kPVi	2.5
kP	0.03	kIVi	5

The secondary control based on the consistency algorithm is essentially an improvement of the traditional sag control, which applies the linear control method to the balancing control. Through the processing of dynamic average voltage and unbalance degree consistency algorithm, the initial reference voltage of sag control is compensated, and the average voltage value of the grid is achieved while ensuring the consistency of unbalance degree through the communication between neighbouring nodes. In the improved method of sag control, the value is calculated using the arithmetic averaging method, and the mean value of the system state quantity is obtained. The deviation signal is then used to compensate the output of the regulation. The reference voltage of the sag control is dynamically adjusted based on the arithmetic averaging method, achieving SOC balance of distributed energy storage units in the grid and balancing the load.

3.2. *Technical Summary*

This research presents a converter control system based on the Boost and Buck-Boost mathematical models according to the urban grid security warning and control strategy, and gives the control strategy for multi-point voltage support of the grid. Simulation experiments validate the stability and reliability of the control system, leading to three main conclusions:

(1) By setting the voltage observer, the voltage reference value of each load node can be dynamically adjusted within the range of load and network parameter changes, and the voltage quality of the network can be improved by reducing the deviation between the bus voltage and the rated value, and the average voltage of the positive and negative buses of the network can be converged.

(2) Based on the voltage observer, adding the use of unbalance controller can make the voltage unbalance of each load node in the network converge, maximize the voltage regulation ability of distributed power supply, reduce the probability of voltage imbalance when the power fluctuation is large, and help to achieve and maintain the power balance of the grid.

(3) The inclusion of consistency control on top of voltage sag control facilitates achieve distributed cooperative control of the grid. This control strategy can flexibly respond to the changing situation of load and communication network, and ensure the normal and stable operation of the load and the whole power grid.

4. Conclusion

The power grid is a complex system that requires careful management and control to ensure its stability and reliability. This is particularly true in the case of distributed power generation systems, which introduce additional challenges due to their decentralized nature. Voltage and power are interrelated and in a stable dynamic equilibrium, which can be controlled by regulating voltage to control power. The main modes of grid operation are grid-connected mode and islanding mode, as well as a transient mode that switches between the two modes. When the grid is grid-connected, the grid provides the reference voltage and frequency, the dynamic characteristics of the DG within the grid are less demanding, the grid control system is relatively simple, and the power quality within the grid is generally better than that of an island during normal operation.[13]

Multiple voltage support points are used to regulate the active and reactive power of the grid, i.e., both the external grid and all controllable power sources are used as voltage support points for the grid system.[14] When the grid is grid-connected, the external grid acts as the only voltage support point for the system; when the grid is operated independently, all controllable power sources act together as the voltage support point for the system. The grid has both grid-connected and islanded operation externally, as well as a variety of flexible operation modes between internal power sources and loads.

Uncontrolled power supplies operate in maximum power point tracking (MPPT) mode. The active power output of these power sources is determined by the external natural environment, i.e., the corresponding electrical energy is generated in accordance with the external energy input (energy conversion), e.g., wind power, photovoltaic power, etc. [15] As the system is highly influenced by external factors, additional controllers are often required to regulate, control, and protect the system in order to ensure a constant rated power output [16].

The energy storage device is only charged and controlled under grid-connected operation conditions, without controlling and regulating the system frequency and voltage, so as to reserve power, thus making the system have higher energy efficiency and lower operating costs. In the event of a major grid failure, the grid is used as a backup power source when operating independently, which reduces the number of times the energy storage device is charged and discharged, reduces the operational energy consumption of the system, increases the service life of the energy storage device and improves the service life of the energy storage device [17]. At the same time, when the grid is running independently, the energy storage device can release electrical energy or purchase power from the grid to ensure the normal operation of the grid, the energy storage device can also achieve the supplement of power shortage and excess power absorption.

Overall, effective control is essential for ensuring the safe and stable operation of distributed power generation systems, and for enabling the transition to a more sustainable and resilient energy future.

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