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Simulation- Based Comparative Analysis of Urban and Rural Grounding System Under Earth Fault Conditions

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A B S T R A C T

Grounding systems play a critical role in ensuring the safety and reliability of electric power systems, especially during fault conditions such as earth faults. The performance of these systems varies significantly depending on geographical and infrastructural factors, especially between urban and rural substations. This study presents a simulation-based comparative analysis of grounding system behavior under earth fault conditions in both urban and rural environments using MATLAB/Simulink. The research investigates how different soil resistivity profiles, grid configurations, and environmental parameters affect key grounding metrics such as earth resistance, step and touch voltages, and fault current dissipation. The urban grounding system, which is characterized by interconnected networks and dense infrastructure, is modeled with multiple grounding electrodes, interconnected cable sheaths, and common bonding networks. In contrast, the rural grounding system, which is typically isolated and exposed to high-resistivity soils, is modeled with simpler grid layouts and limited grounding connections. The simulations include various fault scenarios including single line-to-ground (SLG) and double line-to-ground (DLG) faults. Advanced intelligent algorithms such as fuzzy logic and particle swarm optimization (PSO) are integrated to classify fault types and optimize system response in real-time. Comparative waveform analysis is performed through multiple scopes to assess grounding performance parameters. The results show that urban systems generally sustain low step and touch voltages due to extensive interconnection and low soil resistivity, while rural systems face higher risks due to poor dissipation of fault currents. However, with optimized grounding design and adaptive control algorithms, the performance of rural systems can be significantly improved.

Keywords: Grounding System, Earth Fault, Urban Grounding System, Rural Grounding System, Substation Safety, Ground Potential Rise (GPR),Step Voltage, Touch Voltage, Soil Resistivity,Earthing Grid Design.

1.Introduction

In city centers, urban or industrial areas, grounding systems (GS) are installed in a common field of influence and may be interconnected not only by intentional connections but also by unintentional connections, such as buried metal structures, steel pipes and other external conductive parts that may be present in the same area, so they naturally interact [1]. Mutual interference between non-interconnected GS may arise due to conductive coupling with intentional ground systems. When one GS propagates a ground fault current, it may transfer unexpected touch voltages to another one nearby. The interfering GSs create significant modifications of the ground surface potential near/around the grid [2]. These transferred potentials can give rise to touch and step voltages and ground potential shifts. The standard IEC/EN 61936-1 defines the "global grounding system" (GGS) as a system formed by the interconnection of local GSs that form a quasi-equivalent grounding surface with no dangerous touch voltages [4]. In all types of high voltage substations in urban centres, rural and industrial areas, it is necessary to install a system to effectively connect all metallic structures and non-energised parts of the power system equipment together and to earth so that any potential difference between them is limited to safe values [5]. This system is generally referred to as the "grounding system". Potential differences are the result of ground currents caused by lightning discharges, fault conditions, switching or in-rush currents caused by normal system operation [6]. The passage of these currents through the soil and metal conductors generates high voltages that can be dangerous to human life, and can damage and cause malfunctions of system equipment. The grounding system provides a means of safely discharging lightning currents to earth, reducing step and touch potentials to safe levels and restricting hazardous soil currents to inaccessible areas [7]. It also allows detection of ground fault currents by protective relaying systems, provides a low impedance path through the earth for load currents, and provides a common ground reference that aids in the coordination of insulation throughout the system. Grounding systems are also used to protect control cables and other low voltage wiring from the effects of electromagnetic interference (EMI) and capacitive coupling, which tend to reduce voltages in the grid. Grounding systems help reduce voltages between and among various points along low voltage cables used for control, communications and auxiliary power [8]. Grounding systems are a fundamental part of electric power distribution and transmission infrastructure, ensuring safety, system stability and protection of both equipment and personnel [9]. They play a critical role in safely dissipating fault currents into the earth, particularly during earth fault conditions such as single line-to-ground (SLG) faults. The design and performance of grounding systems varies considerably depending on the geographic and environmental context, with urban and rural settings presenting unique challenges and requirements. The aim of this research is to investigate these differences through a comprehensive simulation approach combined with advanced fault identification techniques to enhance system safety and reliability [10].

2. Litreture Review

G. Paris, et al [1] (2015) In city centers, urban or industrial areas, grounding systems (GS) naturally interact as they share common areas of influence. IEC standard 61936-1 defines a "global grounding system" (GGS) as consisting of elements that are essentially interconnected such as the metal casing of MV cables. This paper deals with the analysis of the parameters that characterize grounding systems as separate electrodes, as they are considered in the design specifications and verification tests suggested by the IEC standards. The paper analyzes the impact of more grounding systems in the same area of influence and their possible global integration.

K.D. Pham, et al [2] (1990) The author presents an analytical approach using digital computers to design safe ground mats for high-voltage substations. Human factor considerations and the calculation of phase and touch potentials and ground fault currents are discussed. Accurate evaluation of ground mat design can be achieved with the use of digital computers, and costly and conservative designs can be eliminated. A summary of all input parameters for the ground mat computer-aided design program and output information is provided. Ground mat construction and grounding system performance follow-up are discussed. A sample ground mat design problem is included.

L. Gresev, et al [3] year (1997) Earth potential rise around high-voltage substations in case of faults can cause dangerous voltages between nearby telephone subscriber lines and neutral ground. In rural and urban areas the substation grounding system may be connected to or located near a large and complex network of conductors composed of power and telecommunication cables, pipes for water, gas and heating, and the metal casings of the rails of the traffic system. Such complex structures may increase the earth potential rise area of influence. This paper presents an analysis of parameters that have a major influence on the earth potential distribution in urban areas.

G. Lessard et al [4] In 2000, the growing use of mobile telephone systems led to the installation of antennas on high-voltage (HV) towers, especially in rural areas with limited infrastructure. These installations raised safety concerns, particularly regarding touch voltages during faults. To power these systems, medium-voltage (MV) lines are used, raising the question of whether the HV and MV grounding systems should be interconnected outside the substation or separated using transformers. Hydro Québec initiated a project involving computer simulations and field tests to determine the safest and most efficient feeding method.

M. Abdaldam, et.al [5] on year (2017) This paper presents the design of 110kV substation grounding grid with high resistivity soil. A horizontal two-layer soil model is built through the MALT program of the software (CDEGS). The aim of this paper is to reduce the touch and step voltages when the resistivity soil is high during a direct lightning strike in an urban substation. The touch and step voltages in the ground surface were calculated based on its soil resistivity in the upper and lower layers. The calculated results are compared with the standard values formulated in the IEEE Guide for Safety in AC Substation Grounding.

C. Matros, et.al [8] on year (2012) German grid operators are facing increasing challenges regarding voltage limitations in grids with a large number of installed PV systems. To allow the development of advanced technical solutions to overcome these challenges and hence increase the potential of installing PV in low voltage distribution grids, a model has been developed to assess voltage levels in grids with different levels of PV penetration. The results show a strong need for voltage control in secondary substations and derive basic guidelines for application as well as development criteria.

J. G. Sverk, et al [9] year (1981) A practical approach to safety in grounding aims to balance the interaction of the two grounding systems: permanent, which includes buried ground electrodes, and accidental, which arises when a person walks or stands in an exposed area and touches a grounded object. This paper describes the conditions and factors encountered in accidental circuit analysis. 80, which is currently being revised by Working Group 78.1 of the Distribution Substation Subcommittee, and is being sponsored by the Substation Committee of the IEEE. After comments are received from industry on Part I, as well as future Parts II, III, IV, a separate document will be qualified as a guide for submitting IEEE standards.

3.Methodology

Photovoltaic cells, assembled into large modules, form a photovoltaic module and are connected in series and parallel to form a photovoltaic system. The output of the photovoltaic modules is connected to an MPPT, which maximizes the power output of the panels. Various MPPT algorithms are available to optimize the performance of photovoltaic systems, including the perturb-observe (PO) algorithm. In this way, a maximum power point (MPP) tracker extracts maximum power from solar photovoltaic modules. Solar energy is converted into electricity by the photovoltaic system. The power of a photovoltaic system varies depending on weather conditions. Therefore, to extract maximum power from a photovoltaic system, it is connected to a maximum power point tracking (MPPT) system. Since photovoltaic power sources generate electricity at low, variable DC voltages, they require energy processing before connecting to a DC line. For this purpose, a DC-DC converter is used. The output of the converter is connected to a DC link capacitor, which in turn is connected to the power grid via an inverter. The output voltage is taken from the mains to provide a voltage slightly higher than the mains voltage for additional power. "Three-phase grid-connected electrical converters are only considered for grid-connected applications where a cooperative energy storage system is not required." Three-phase power converters are typically used for high power applications, however the project aims to encourage individual households to use grid-connected three-phase electrical converters. The MPPT controller operates in "P&O" mode. This MPPT system automatically adjusts the DC reference signal from the inverter's constant voltage regulator to obtain a stable voltage that maximizes the solar panel's output power. The MPPT controls the inverter, operating the panel at its maximum power, regardless of the many possible load impedance adjustments.

4. Result & Discussion

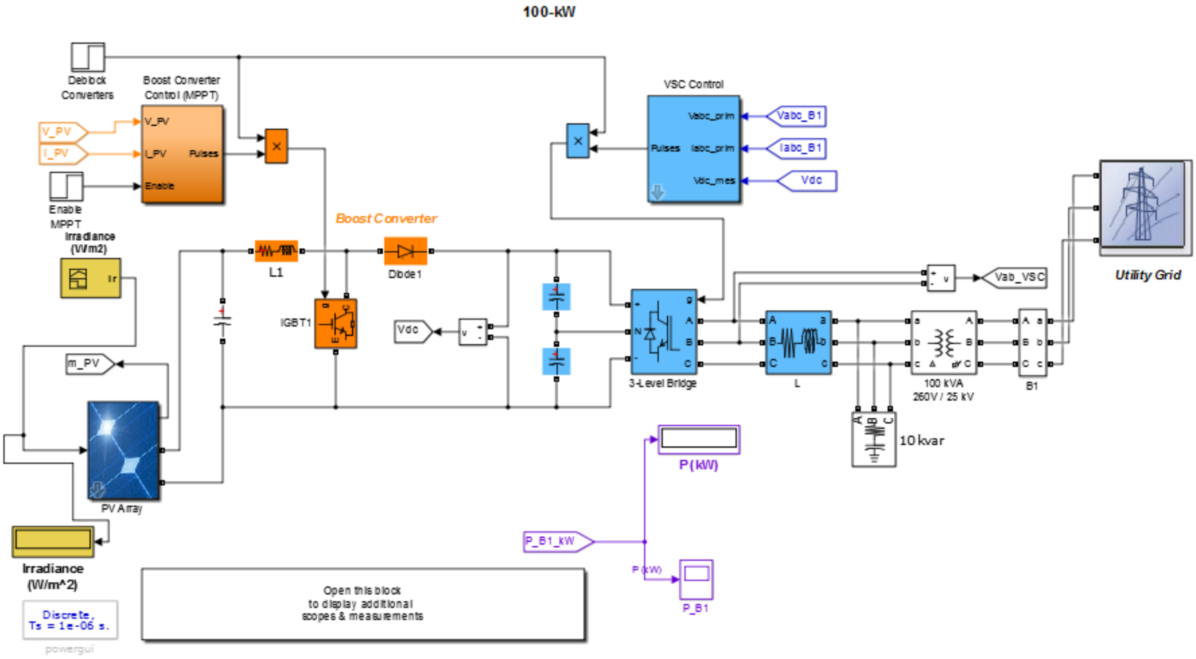

Figure 1. Simulation modal under no earth fault condition

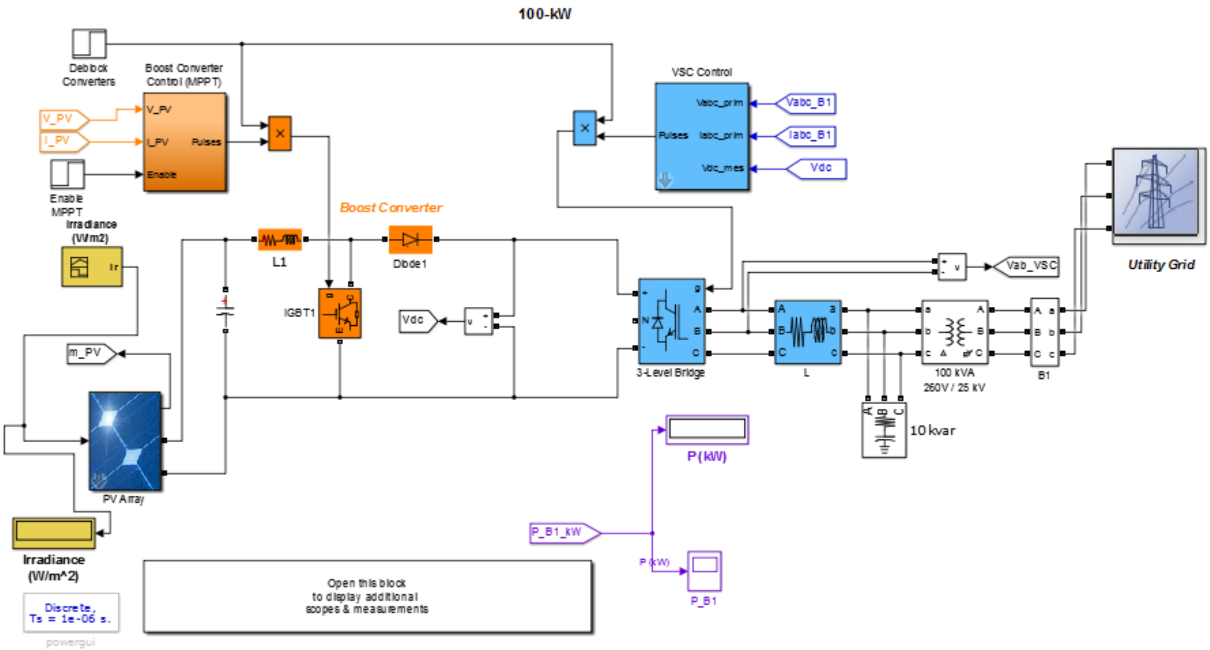

Figure 2. Simulation modal under earth fault condition

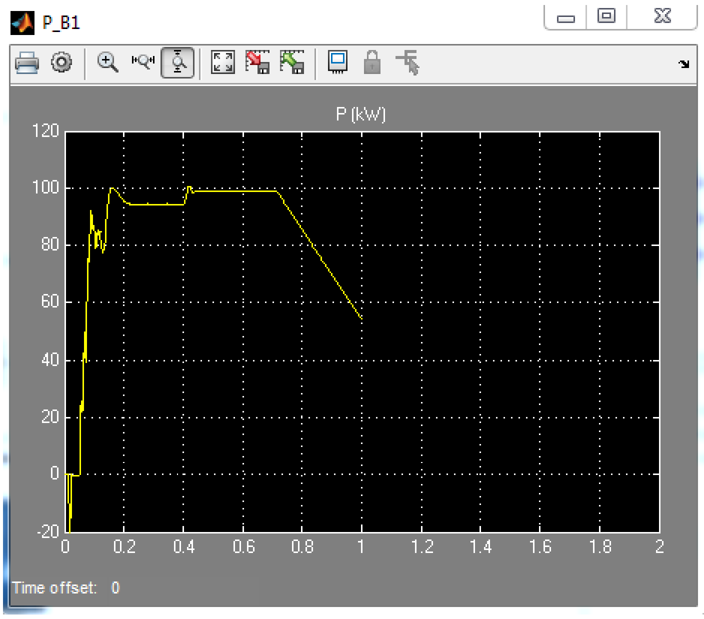

Figure 3. Output power under no earth fault condition

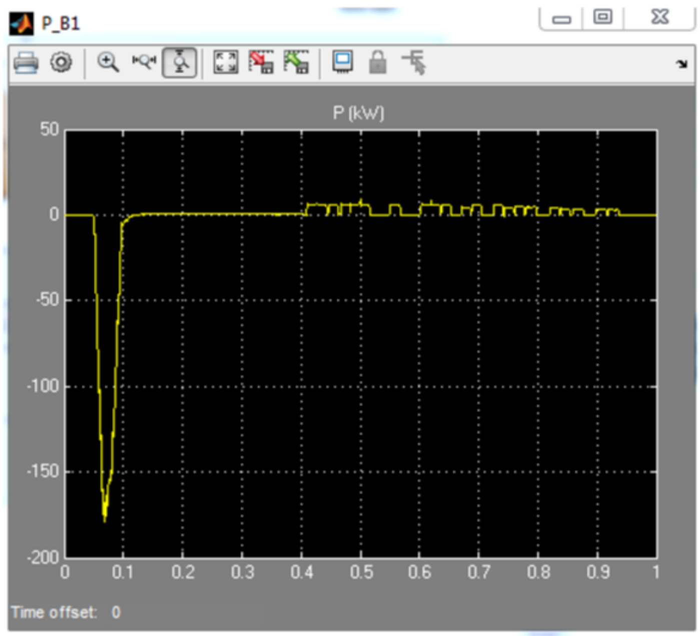

Figure 4. Output power under earth fault condition

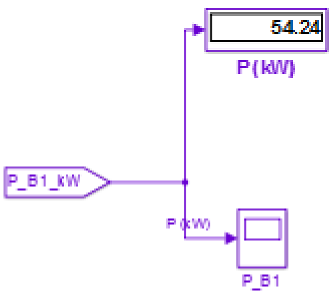

Figure 4. Output power(54.24 KW) under no earth fault condition

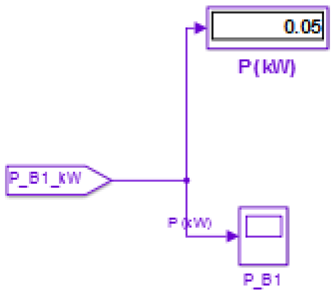

Figure 5. Output power(0.05 KW) under earth fault condition

5. Conclusion

Simulation-based comparative analysis of urban and rural grounding systems under earth fault conditions highlights significant differences in system behavior, safety margins, and fault current dissipation capabilities. Urban grounding systems, which are often interconnected through infrastructure and metallic networks, show lower impedance and more effective fault current dispersion due to denser electrode configurations. In contrast, rural systems face challenges such as high soil resistivity, sparse grounding structures, and increased step and touch voltages, requiring more robust and adaptive grounding designs. Through MATLAB/Simulink modeling and waveform analysis, the study confirms that urban systems provide better protection against earth faults, but may also cause unintended current paths due to shared grounding zones. Incorporating intelligent fault classification algorithms such as fuzzy logic or PSO can improve fault detection and classification in real time. Ultimately, this research contributes to safer, more efficient substation grounding practices in a variety of environments, supporting the development of future smart grid infrastructure. Figure 1. Shows the simulation model without earth fault condition. Figure 2. Shows the simulation modal under earth fault condition . Figure 3. Shows the output power without earth fault condition. Figure 4. Shows the output power (54.24 kW) without earth fault condition. Figure 5. Shows the output power (0.05 kW) under earth fault condition.

6. Future Scope

1.A**dvanced Fault Detection Algorithms**: Future studies should incorporate intelligent methods like Fuzzy Logic, ANN, SVM, and PSO to improve fault classification accuracy and enable real-time detection in complex systems.

2.Field Validation: Real-time data collection from substations—measuring earth resistance, step, and touch voltages—will help validate simulation results and enhance practical reliability.

3.**Enhanced Soil Modelling**- Incorporating layered and non-uniform soil profiles, along with seasonal variations in soil properties, will result in more accurate and site-specific grounding system designs.

4.**Transient and Frequency Analysis**: Tools like EMTP and COMSOL should be used to simulate switching surges and lightning effects, providing a deeper understanding of grounding behaviour under high-frequency and transient conditions.

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