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Power System Surges: Causes, Effects, and Mitigation Strategies

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Abstract- Electrical power system surges represent a significant challenge in both residential and industrial settings, affecting the reliability and safety of electrical networks. This paper examines the fundamental causes of electrical surges, the potential effects on power systems and sensitive equipment, and various mitigation strategies aimed at preventing surge-induced damages. With the increasing reliance on sophisticated electronics and the growing complexity of power systems, understanding the dynamics of surges is crucial for engineers and utility operators to maintain power quality. A Resistor-Inductor-Capacitor (RLC) circuit, Telegrapher's Equation, Double-Exponential Function, and Laplace Transform were used as modelling techniques. Conclusively, connecting surge absorbers and surge diverters in parallel is the preferred method for enhancing the performance and reliability of a surge protection system and by adopting a multi-layered protection strategy including Surge Protection Devices (SPDs), proper grounding, and advanced monitoring technologies, power systems can maintain reliability and protect both equipment and infrastructure from surge-induced damage. As electrical systems continue to evolve, integrating smarter, more predictive technologies will further enhance surge protection and ensure the continued resilience of the power grid.

Keywords- Advanced Monitoring Technologies, Electrical Power, Surge Absorbers, Surge Diverters, Surge Protection Devices

I. INTRODUCTION

Electrical power systems are designed to deliver consistent, reliable voltage to end-users. However, various factors, both natural and man-made, can cause momentary surges in voltage, known as power system surges. These surges, although transient, cause equipment damage, data loss, and, in severe cases, system-wide outages. The increasing prevalence of sensitive electronic devices has made surge protection an essential aspect of power system design and operation. This paper discusses the characteristics of electrical surges, their causes, and their implications for power system reliability, as well as mitigation techniques to protect against them.

Just as no human can survive without the flow of blood, no nation or city can thrive without reliable electricity. Developed nations have harnessed consistent electricity to achieve and maintain their current status. Today, they enjoy years of uninterrupted power supply, which has enabled their industries, utilities, hospitals, and schools to provide comfortable living conditions for their citizens. It is evident that no country can transition from underdevelopment to development without access to reliable electricity; without reliable electricity, there can be no development. Sustainable progress has continued to elude

Nigeria as a nation due to its lack of dependable electricity (Ibinabo and Ijeoma, 2019).

Electrical energy has countless applications in homes, industries, agriculture, and transportation. In economically developing countries like Nigeria, the demand for electrical power is increasing rapidly. As a result, power distribution networks are becoming heavily loaded, which has made the development of effective protection schemes a significant concern for many substations within these networks. Numerous studies have been conducted on electric power distribution protection, and various solutions have been proposed to enhance the protection of distribution networks (Ijeoma and Amadi, 2024).

Hachimenum et al. (2025) explains that a power distribution unit (PDU) is a device with multiple outputs designed to distribute electric power, particularly to racks of computers and networking equipment within a data center. Data centers encounter challenges related to power protection and management solutions. Therefore, many data centers utilize PDU monitoring to enhance efficiency, uptime, and scalability. PDUs come in various forms, ranging from simple and cost-effective rack-mounted power strips to larger floor-mounted units that offer multiple functions, including power filtering for improved power quality, intelligent load balancing, and remote monitoring and control via Local Area Network (LAN) or Simple Network Management Protocol (SNMP).

Electrical surges are among the most common and potentially damaging disturbances in power systems. These transient overvoltages can harm sensitive electronic equipment, shorten the lifespan of appliances, and even lead to complete system failures. Although surges typically last only for a brief period, their effects can be long-lasting and costly, especially in modern societies that rely heavily on electronic systems (Ijeoma and Nwauzi, 2019).

Osahenvemwen et al. presented a paper on the phenomenon of electrical surges in power distribution networks and its impact on the quality of power supplied to customers. The study involved three major steps. First, lightning surge detectors were installed in six residences and monitored over a period of three years, from 2013 to 2015.

The interaction between electric power and electrical equipment results in power quality measurements (Dharmender, 2014). Power quality can be assessed by considering the uninterrupted supply of electricity. This can be achieved by ensuring that wiring, grounding, and bonding meet required standards. Once these standards are verified, suitable power quality devices can be selected, such as Surge Protective Devices (SPDs), low-pass filters, and signal line protectors, to safeguard against damage from surges and electrical noise.

Surges or overvoltages have caused significant stress, disruptions, and damage to various equipment and devices within the Ajaokuta Power System network. This includes high and low voltage induction motors, synchronous motors, transformers, circuit breakers, reactors, capacitor banks, generators, contactors, and relays. Khalid and Bharti (2011) highlighted power quality issues, including power surges in relation to international standards, the impact of power quality problems on electrical apparatus, and methods of correction.

Shehab (2013) presented a model regarding lightning strikes and their effects on electrical power distribution systems, particularly focusing on the output and overall impact when lightning arresters are present. Protective devices are used to safeguard against excessive fault currents in electric power distribution systems, and circuit breakers are tripped by overcurrent protection relays (Okundamiya et al., 2009). These protection relays are activated after allowing two or three cycles of fault current to pass through, which introduces a response-time delay.

The Superconducting Fault Current Limiter (SFCL) is an innovative device designed to reduce fault current levels within the first cycle of a fault. The application of fault current limiters (FCLs) not only decreases stress on network devices but also enhances the reliability of the power system, as indicated by Makinde et al. (2014).

Degradation, disruption, and destruction are three factors that impact power quality. Electrical power supply abnormalities are often referred to as surges, transients, or electrical line noise, which are deviations from the normal voltage supply (Gustavo et al., 2003; Sukhdeo & Prasada, 2013). These electrical power abnormalities can occur for a short period or continuously over time. A surge is essentially a transient power or over-voltage in an electrical circuit. In power systems, a surge or transient is defined as an over-voltage that lasts for less than half a cycle of the normal voltage waveform. Surges can have either negative or positive polarity and can be characterized as either additive or subtractive relative to the normal voltage waveform, often displaying decaying and oscillatory characteristics. Surge voltages can destroy, degrade, or damage electronic equipment in both commercial and residential buildings due to disturbances in the power waveform or over-voltage spikes (Khalid & Bharti, 2011; Teru, 2010).

II. MATERIALS AND METHOD

A mathematical model of electrical power system surges describes the transient behavior of overvoltage and overcurrent in a power system caused by switching actions, lightning strikes, or faults. These surges can be analyzed using differential equations, Laplace transforms, and circuit modeling techniques.

1. Mathematical Models

Basic Surge Equation (LCR Model)

A power system can be modeled as an RLC circuit (Resistor-Inductor-Capacitor), where the surge propagation follows the appropriate equations:

$$L\frac{dI}{dt} + RI + \frac{1}{C}\int I\,dt = V_s(t) \quad (1)$$

Where:
L = Inductance (H)
R = Resistance (Ω)
C = Capacitance (F)
I = Surge current (A)
Vs (t) = Surge voltage source (V)
Taking the derivative:

$$L\frac{d^2I}{dt^2} + R\frac{dI}{dt} + \frac{1}{C} = \frac{dV_s}{dt} \quad (2)$$

$$V_C = \frac{1}{C}\int i\,dt \quad (3)$$

$$i = C\frac{dV_s}{dt} \quad (4)$$

Voltage across R is VR = $Ri = RC\frac{dV_C}{dt}$ (5)

Voltage across L is VL = $L\frac{di}{dt}$ (6)

We can rewrite as:

$$LC\frac{d^2V_C(t)}{dt^2} + RC\frac{dV_C(t)}{dt} + V_C(t) = V_s(t) \quad (7)$$

Using Laplace transforms, initial conditions = 0

$$V_s(s) = sRCV_C(s) + S^2LC\,V_C(s) + V_C(s) \quad (8)$$

$$\frac{V_C(s)}{V_S(s)} = \frac{1}{sRC + S^2LC + 1} \quad (9)$$

Assuming a value of
R = 200 ohms
L = 40mH
C = 1μF

Matlab code:
```
L = 0.040;
C = 0.000001;
R = 200;
NUM = 1;
DENUM = [L*C R*C 1]
G = tf (NUM, DENUM)
Step (G)
```

This second-order differential equation describes the transient response of a surge within the system.

Travelling Wave Model (Telegrapher's Equation)

For long transmission lines, surge behavior is more accurately modeled using the wave equation derived from the telegrapher's equations.

$$\frac{\partial^2 V}{\partial x^2} = LC\frac{\partial^2 V}{\partial x^2} + RC\frac{\partial V}{\partial t} \quad (10)$$

Where:
x = Distance along the transmission line
V (x,t) = Voltage at position x and time t
For lossless lines (R = 0), this reduces to a wave equation:

$$\frac{\partial^2 V}{\partial x^2} = LC\frac{\partial^2 V}{\partial x^2} \quad (11)$$

This explains how voltage surges move as travelling waves at a certain speed:

$$v \frac{1}{\sqrt{LC}} \quad (12)$$

Lightning Surge Model (Double-Exponential Function)

Lightning surges are commonly modelled using a double-exponential function.

$$V(t) = V_0(e^{-\alpha t} - e^{-\beta t}) \quad (13)$$

Where:
V_0= Peak voltage
α, β = Decay constants (determined from rise and fall times)
The generally accepted timing for αβ is 8μs for the rise time and 20μs for the fall time.
For an assumed 33 kV transmission line, the rise time is 8 μs and the decay time is 20 μs.

$$V(t) = V_0(e^{-8t} - e^{-20t}) \quad (14)$$

For a total time of 1s
Matlab code

```
t = 0:0.001:1;
V= 33000*exp(-8*t) - exp(-20*t);
plot(t,V)
xlabel('surge time')
ylabel('AMplitude of lightning Voltage')
title('Lightning Surge Graph')
```

This describes a rapid pulse that rises quickly, followed by a slower decay, which is characteristic of surges induced by lightning.

Frequency-Domain Representation (Laplace Transform)

The surge response can be examined in the frequency domain using the Laplace Transform:

$$V(s) = \frac{V_0}{(s+\alpha)(s+\beta)} \quad (15)$$

Here, s represents the complex frequency variable, which aids in analyzing resonance and damping effects in surge protection devices.

2. Understanding Electrical Power System Surges

Definition and Characteristics

An electrical surge is a brief, high-voltage event that occurs when the flow of electricity is interrupted and then restarted, or when a large amount of electricity is suddenly introduced into the system. Although surges usually last only a few microseconds, the voltage spike can be significantly higher than the normal operating voltage.

Causes of Surges

Power Surges can be classified based on their Source

External Causes: These surges originate from outside the facility and include events such as lightning strikes, grid-switching activities, and faults in the power grid. Lightning, in particular, can introduce millions of volts into power lines, overpowering protective systems.

Internal Causes: These surges occur within the facility and are typically caused by the operation of high-power devices, such as motors and compressors, as well as by switching devices that generate transient over-voltages. Additionally, changes in load or faulty wiring can also contribute to internal surges.

Types of Surges

- **Transient Surges:** These are short-lived events often caused by lightning or switching operations and are characterized by high-energy pulses.
- **Overvoltage Conditions:** Sustained overvoltage can occur due to grid faults or poor voltage regulation in the power distribution system.

3. Effects of Power System Surges

Impact on Equipment

Power system surges are particularly damaging to sensitive electronic devices such as computers, servers, and telecommunication systems. Even small surges can cause cumulative damage to microchips and other components, reducing the lifespan of equipment. Large surges, such as those caused by lightning strikes, can result in immediate failure or destruction of electrical devices.

Degradation of Power Quality

Frequent surges degrade overall power quality, leading to issues such as voltage sags, swells, harmonic distortion, and flickering lights. Poor power quality affects industrial processes, reduces efficiency, and can lead to costly downtime.

Safety Hazards

High-energy surges can damage the insulation of electrical cables, potentially leading to short circuits or electrical fires. In extreme cases, surges can trip breakers, disable safety systems, and create conditions conducive to electrical accidents.

4. Surge Mitigation Techniques

Surge Protection Devices (SPDs)

SPDs are devices designed to protect electrical systems and equipment by diverting excess voltage to the ground. They are categorized into three types:

- **Type 1 SPDs:** Installed at the service entrance, these devices protect against external surges, such as those from lightning or grid switching.
- **Type 2 SPDs:** Installed at distribution boards, these protect against internally generated surges.
- **Type 3 SPDs:** Installed at the point of use (e.g., at the socket or plug), these offer localized protection for sensitive devices.

Whole-House Surge Protection

For residential and commercial buildings, whole-house surge protectors installed at the main service panel provide an initial layer of defense against external surges. These systems are effective at absorbing and dissipating large surges before they reach internal circuits.

Proper Grounding and Bonding

Effective grounding and bonding are essential for mitigating surges. A low-impedance ground path enables excess surge energy to safely dissipate into the earth, which helps reduce the risk of equipment damage. It is crucial to ensure that the grounding system complies with relevant standards for optimal surge protection.

Advanced Power Conditioning Equipment

Power conditioning devices, such as uninterruptible power supplies (UPS) and voltage regulators, help manage power fluctuations. A UPS, for example, provides temporary power during surges or outages, ensuring that critical systems continue to operate without interruption. Voltage regulators stabilize the incoming voltage, reducing the impact of both surges and sags.

5. Technological Advancements in Surge Protection

Smart Grid Integration

As power grids become more interconnected and digital, smart-grid technology is being implemented to monitor and control electricity flows in real time. This advancement allows for quicker detection of surge events and more effective mitigation by dynamically adjusting grid operations, helping to minimize the impact on downstream equipment.

Internet of Things (IoT) and Data Analytics

IoT-based monitoring systems can provide continuous tracking of power quality parameters, including surge events. Advanced analytics can be applied to predict potential surge risks and optimize the placement of surge protection devices across power networks.

6. Standards and Regulations for Surge Protection

Various standards exist to guide the design and implementation of surge protection systems. IEEE 1100 (Emerald Book), IEEE C62.41, and IEC 61643 provide guidelines on surge protection device requirements and testing. Compliance with these standards ensures that SPDs are adequately rated to handle specific surge environments and that they provide the intended level of protection.

III. RESULTS AND ANALYSIS

The graph in Figure 1 illustrates that when a surge occurs, the system takes approximately 2 milliseconds to stabilize. This surge causes a disturbance in the system, increasing the voltage to about 1.2 times its original level.

```
DENUM =

    0.0000    0.0002    1.0000


G =

              1
  -------------------------
  4e-08 s^2 + 0.0002 s + 1

Continuous-time transfer function.
```

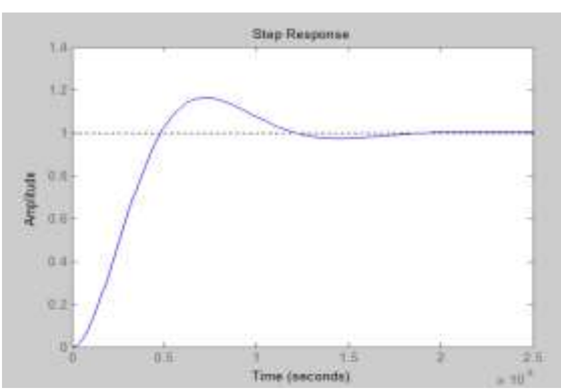

Figure 1: Step response

Figure 2 illustrates the surge in the system, showing that the system voltage peaked at 10 times during the surge. It took approximately 0.6 seconds for the system to normalize after the surge.

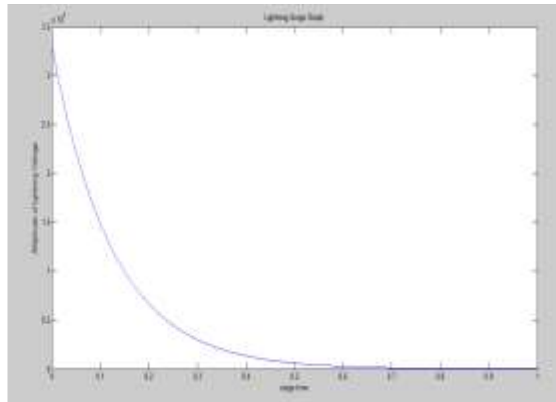

Figure 2: Lightening Surge graph

1. Parallel and Series Connection of Surge Absorbers and Diverters

Surge Absorbers in Parallel

Enhanced Protection Capacity: When multiple surge absorbers, such as metal oxide varistors (MOVs) or transient voltage suppressors (TVS), are connected in parallel, they share the surge current. This setup effectively increases the overall energy-handling capacity of the system. By distributing the surge energy among several devices, each device handles only a portion of the total energy, which helps prevent any single unit from becoming overloaded.

Faster Response: Connecting devices in parallel can lead to a quicker response time because the load is distributed, creating multiple pathways for current dissipation. This arrangement reduces the risk of system failure or equipment damage, especially during high-energy surge events.

Redundancy: If one surge absorber fails, the other devices connected in parallel can continue to provide protection. This redundancy enhances the reliability of the system and prevents complete surge protection failure due to the malfunction of a single component.

Surge Diverters in Parallel

Higher Current Handling: Just like with surge absorbers, connecting surge diverters (also known as surge arresters) in parallel increases the overall current-handling capability. This is particularly useful in systems where large surges (e.g., from lightning strikes) are expected. Multiple parallel surge diverters will divide the surge energy, reducing the stress on each device.

Localized Protection: Surge diverters can be placed at multiple points in parallel, such as at the main power entry and key distribution points, to provide localized protection. This setup ensures that surges are mitigated at various points before they can propagate through the system and reach sensitive equipment.

Advantages of Parallel Connection

Increased Capacity: The system can handle larger surges, ensuring that all excess energy is dissipated without overloading a single device.

Better Performance: For larger and more complex systems, parallel configurations improve overall system robustness by providing multiple protection paths.

Series Connection: Surge Absorbers in Series

Surge absorbers are generally not connected in series for a couple of key reasons:

Voltage Sharing: When surge absorbers are connected in series, the voltage across each device needs to be evenly distributed. If the devices are not perfectly matched, one may end up taking on more voltage than the other. This imbalance can lead to excessive stress on one device, increasing the risk of failure.

Slower Response: In a series configuration, surge absorbers may react more slowly. This is because the voltage must rise to the combined clamping voltage of all devices before the system activates. This delay can leave the protected equipment vulnerable to potentially damaging voltages.

Surge Diverters in Series

Surge diverters are also not connected in series. In a series configuration, the total voltage needs to exceed the combined voltage thresholds of all devices before they become active. This would reduce the effectiveness of the surge protection, as the system may fail to respond to lower-magnitude surges that would otherwise be harmful.

Why Parallel is Preferred for Surge Protection

Improved Energy Dissipation: Connecting surge absorbers or diverter in parallel provides more pathways for the excess energy from a surge to be safely dissipated. This makes the system more robust in handling larger surges.

Redundancy and Reliability: If one protection device fails, the parallel connection ensures that other devices still function, maintaining protection.

Balanced Load: Parallel connections distribute the surge current across multiple devices, preventing any single unit from being overwhelmed.

Best Practices for Surge Protection

Layered Protection Strategy: A combination of surge absorbers and surge diverters at different levels of the system (service entrance, distribution boards, and point-of-use) should be used in parallel configurations. This ensures that surges are mitigated at multiple points, providing comprehensive protection.

Appropriate Sizing: When using multiple devices in parallel, they must be properly rated to ensure that each can handle its share of the surge current and that they respond consistently.

IV. CONCLUSION

Electrical power system surges are an unavoidable aspect of modern electrical systems, but their damaging effects can be significantly reduced with the right surge protection measures. Parallel Connection: Surge absorbers and surge diverters should be connected in parallel to enhance the capacity and reliability of the surge protection system. This configuration allows multiple devices to share the surge load, resulting in faster response times, improved energy dissipation, and added redundancy. Series Connection: Connecting surge absorbers or surge diverters in series is not advisable, as this can lead to slower response times and uneven voltage distribution, ultimately diminishing the effectiveness of the surge protection system. Conclusively, the preferred method for improving the performance and reliability of a surge protection system is to connect surge absorbers and surge diverters in parallel. Additionally, adopting a multi-layered protection strategy that includes surge protective devices (SPDs), proper grounding, and advanced monitoring technologies can help maintain the reliability of power systems and protect both equipment and infrastructure from surge-induced damage. As electrical systems continue to evolve, the integration of smarter, more predictive technologies will further enhance surge protection and ensure the ongoing resilience of the power grid.

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