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Investigation of Electromagnetic Transient in Power Systems Using E.M.T.P. - R.V

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ABSTRACT

Over the years, electromagnetic transient in power systems has been of great concern to the power industries. This is because its effect on transmission lines is enormous. Various research works have been conducted in which several controllers were utilized to enhance the stability of modern power systems. Therefore, the investigation of electromagnetic transient in power systems using Electro-Magnetic Transient Program – Restructured Version (E.M.T.P. –R.V.), which is a comprehensive analysis of transient stability issues, proposed mitigation strategies, and evaluation of the impact of renewable energy integration system stability using simulation studies have been presented. Lightning and switching surges are the dominant and most frequent causes of power system outages. These outages have significant effect on the economy. The protection of electrical systems against electromagnetic transients caused by lightning and switching surges is especially difficult because of the unpredictability of the transients and complexity of their interaction with the electrical systems. Lightning transient that propagates through transmission lines affecting equipment and causing insulation breakdown, needs to be properly handled to minimize its effect of instability on our transmission lines. The arrester investigated is the Zinc Oxide (ZnO) arrester.

1. INTRODUCTION

The operation of an electrical power system involves continuous electromechanical and electromagnetic distribution of energy among the system components. During normal operation under constant load and topology, these energy exchanges are not modeled explicitly, and the system behavior can be represented by voltage and current phasors in the frequency - domain. However, following switching events and system disturbances, the energy exchanges subject the circuit components to higher stresses resulting from excessive currents or voltage variations, the prediction of which is the main objective of power system transient simulation.

It does not however give the time frame for specific phenomena, control resonance, sub - synchronous resonance, Ferro resonance, Transient Recovery Voltage (TRV), Switching over voltage (SOV), etc., nor show the many causes. The transients on one hand involve predominantly interactions between the magnetic fields of inductances and the electric fields of capacitance in the electrical system; they are referred to as "Electromagnetic Transients (Dommel, 1969)'. On the other hand, transients are mainly affected by interactions between the mechanical energy

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stored in the rotating machines and the electrical energy stored in the network; they are accordingly referred to as 'Electromechanical transients' (Dommel, 1969). There is a grey area in the middle, namely the transient stability region, where both effects play a part and may need adequate representation.

In general, the lightning stroke produces the highest voltage surges and, thus, determines the insulation levels. However, at operating voltages of 400kV and above, system-generated over voltages, such as those caused by energizing the transmission lines, can often be the determining factor for insulation coordination (Dommel, 1969).

Electromagnetic transients can have high-frequency components and fast rise times, which can propagate through the electrical network and affect the behavior of the system. They can cause voltage and current distortions, equipment damage, insulation breakdown, and operational issues if not properly managed.

Electromagnetic transients encompass a wide range of phenomena, including:

Switching Transients: These occur when switching operations, such as opening or closing of circuit breakers, occur in the electrical system. Switching transients can lead to rapid changes in voltage and current levels, causing voltage spikes, ringing, and oscillations.

Fault Transients: When a fault, such as a short circuit or ground fault, occurs in the power system, it can result in sudden changes in current and voltage levels. Fault transients can cause high fault currents, voltage dips, and system instability.

Lightning Transients: Lightning strikes near power lines or equipment can induce high-voltage surges in the system. These lightning transients can propagate through transmission lines, affecting equipment and causing insulation breakdown.

Load Transients: When large inductive or capacitive loads are switched on or off in the system, it can lead to transient responses. Inductive loads can produce voltage dips, while capacitive loads can cause voltage surges.

Over the years, many works have been carried out in the analysis and understanding of electromagnetic transients in power systems. Researchers focused on developing mathematical models, simulation techniques, and measurement methods to study transient behavior. Kundur et al. (2016). Investigated the transient stability of power systems with high renewable energy penetration. They addressed the challenges posed by the integration of intermittent renewable energy sources and proposed techniques to enhance transient stability during system disturbances.

Baranov et al. (2019). focused on the analysis of electromagnetic transients in micro grids with distributed energy resources (D.E.R.s). They explored the impact of D.E.R.s on system transients and proposed modeling approaches to accurately represent the behavior of D.E.R.s in a transient simulation.

Tolbert et al. (2022). addressed the protection of power electronics devices in the presence of transients. It investigated advanced protection strategies and devices to mitigate the effects of transients on power electronic converters and improve their robustness during transient events.

Gole et al. (2020). focused on the mitigation of transient over voltages in power systems using surge arresters. They explored the performance of surge arresters in reducing over voltages caused by lightning strikes, switching operations, and other transients.

However, the research of lightning transient on the transmission line using Electro-Magnetic Transient Program – Restructured Version (E.M.T.P. –R.V.), to simulate and analyze result particularly with the Zinc Oxide (ZnO) arrester has not been thoroughly looked into, which is where our project work will focus on.

1.1 Zinc Oxide Arrester

A zinc oxide lightning arrester is a device used to protect electrical equipment and installations from the damaging effects of lightning strikes. It operates based on the principle of voltage clamping and diversion of lightning current. It consists of a porcelain housing or tube filled with zinc oxide elements. The housing is usually cylindrical with metal end fittings for electrical connections. The zinc oxide elements inside the arrester provide voltage clamping characteristics. Under normal operating conditions, the arrester presents a high resistance to the flow of current, allowing normal system voltage to pass through unaffected. When a lightning strike or surge occurs on the power line, the voltage across the arrester increases significantly beyond the normal system voltage. The increased voltage causes the zinc oxide elements to break down, transitioning from a high-resistance state to a low-resistance state.

This transition happens rapidly (in microseconds) due to the nonlinear characteristics of the zinc oxide material. Once the breakdown occurs, the arrester effectively provides a low-impedance path to divert the lightning current. The majority of the current is directed through the arrester, bypassing the protected equipment or installation. As the current flows through the arrester, its impedance limits the voltage rise, preventing the voltage from exceeding a predetermined safe level. This voltage limitation ensures that the protected equipment is not subjected to excessive voltage stress. After the lightning surge passes, the zinc oxide elements return to their high-resistance state, ready to protect against the next surge. However, in some cases, if the surge is severe or repeated, the arrester may suffer damage and require replacement. It's important to note that the operation of a zinc oxide lightning arrester is more complex, involving various factors such as the arrester's rating, coordination with other protective devices, and the overall grounding system. Professional installation, maintenance, and periodic testing by qualified personnel are necessary to ensure the effective performance of lightning arresters.

Furthermore, the zinc oxide arrester, also known as a surge arrester or lightning arrester, is a protective device used in electrical power systems to safeguard sensitive equipment from voltage surges or transient over voltages. These over voltages can be caused by lightning strikes, switching operations, or other disturbances in the power grid.

The zinc oxide arrester is typically made up of a series of metal-oxide varistors (MOV) connected in parallel. Each MOV consists of a ceramic disk made of zinc oxide material with metal electrodes attached to its surfaces. When the voltage across the arrester is below a certain threshold, the MOV exhibits high resistance, allowing only a small leakage current to pass through. However, when the voltage exceeds the threshold, the MOV rapidly changes its resistance and becomes highly conductive, diverting the excess current to the ground.

Fig 1: Zinc Oxide Arrester [8]

1.2. EMTP-RV

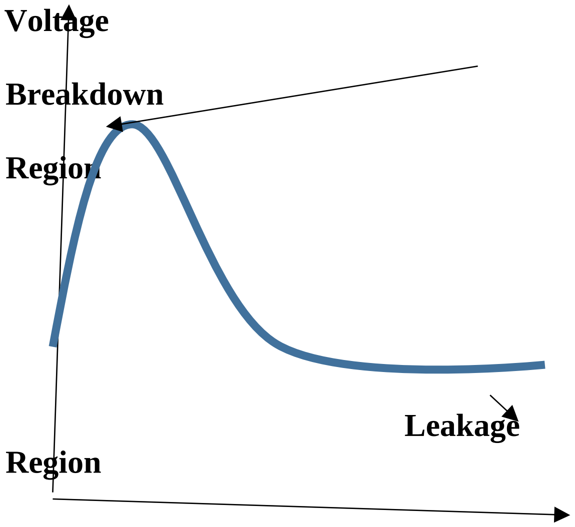
Electro-Magnetic Transients Program (EMTP) family is often used in lightning performance analysis of power systems.

For the case of a direct lightning strike to the transmission line shield wire or to the steel tower, the most important are mathematical models of the transmission line
and the surge arrester (Mohan, et al., 1994). Transmission line models with their frequency-dependent proximity and skin characteristics, time-dependent
and voltage-dependent model of insulation gaps,
and nonlinear corona model are implemented in
mathematical models of power system components as the main operating principles of EMTP-RV (Mohan, et al., 1994).

In EMTP-RV we have also a few models of surge arresters, but for more complicated systems some problems of lightning overvoltage simulations are observed as numerical instabilities of solutions or interrupted simulations. Such simulations for
the first positive 10/350 µs and for the subsequent negative 0.25/100 µs short stroke currents can connected with ZnO arrester and the substation
models.

EMTP-RV control devices can be used to model arbitrary power system elements.

In figure 6, the voltage is plotted on the y-axis, and the current on the x-axis. The graph illustrates the response of the zinc oxide arrester to increasing voltage**.**



Current

Fig 2 shows the voltage– current characteristics

Leakage Region: When the voltage is below the threshold level (represented by the bottom part of the graph), the arrester is in the leakage region. In this region, the arrester exhibits high resistance, allowing only a minimal current (leakage current) to pass through. The leakage current is typically in the range of micro amps (µA).

Breakdown Region: As the voltage exceeds the threshold level, the arrester enters the breakdown region. In this region, the arrester rapidly changes its resistance and becomes highly conductive. As a result, a large amount of current can flow through the arrester, diverting the excessive voltage to the ground. The breakdown region is represented by the steep upward slope in the graph.

Clamping Voltage: The clamping voltage is the voltage level at which the arrester starts conducting significant current. It is the voltage level at which the arrester provides effective protection against over voltages. In the breakdown region, the arrester clamps the voltage at a relatively constant level, preventing it from reaching the protected equipment.

It's important to note that the graph represents the idealized behavior of a zinc oxide arrester. In reality, there may be variations in the characteristics depending on the specific design and manufacturing of the arrester.

Zinc oxide arresters are widely used in power systems due to their excellent protective capabilities, fast response time, and ability to handle high-energy transients. They provide a crucial line of defense for sensitive electrical equipment, ensuring their safe operation and minimizing the risk of damage caused by voltage surges.

The values of voltage and current plotted in the graph of a zinc oxide (ZnO) arrester can vary depending on the specific characteristics and ratings of the arrester. However, I can provide a general idea of the voltage and current ranges typically seen in the graph.

Voltage: The voltage range typically plotted on the y-axis of the graph can vary, but it usually covers a wide range to accommodate the various voltage levels encountered in power systems. It can start from a few volts and extend up to several kilovolts or even higher. The exact values would depend on the specific application and the voltage rating of the arrester.

Current: The current range plotted on the x-axis of the graph can also vary depending on the specific arrester. In the leakage region, where the arrester exhibits high resistance, the current is typically in the range of micro amps (µA), representing the small leakage current. In the breakdown region, where the arrester becomes highly conductive, the current can increase significantly. It can range from a few milliamps (mA) to several amps (A) or more, depending on the arrester's design and the magnitude of the voltage surge.

It's important to note that the exact voltage and current values plotted on the graph will depend on the specific manufacturer, model, and rating of the zinc oxide arrester. Therefore, it's recommended to refer to the manufacturer's datasheet or specifications for precise values related to a particular arrester.

2. METHODOLOGY

Researches on transient lightning have been few and the stability and disturbance problems persist in the system. This study is focused in the use of EMTP-RV software to simulate and analyze Zinc Oxide (ZnO) arrester in discharging the lightning strike experienced by the power system. Various parameters were varied to see its effectiveness.

During simulation using Electro-Magnetic Transient Program – Restructured Version (E.M.T.P. –R.V.) tool, we adjusted the following parameters involved in the lightning arrester transients:

- Voltage Rating: The lightning arrester is designed to withstand a certain maximum voltage level. This rating represents the highest voltage the arrester can handle without breaking down or sustaining damage.
- Energy Absorption: Lightning arresters are designed to absorb and dissipate the energy associated with lightning strikes or transient over voltages. The energy absorption capability is an important parameter, as it determines the arrester's ability to protect the system.
- Response Time: The response time of a lightning arrester refers to the time it takes for the arrester to start conducting current and diverting the surge away from the protected equipment. A faster response time is generally desired to minimize the exposure of the system to transient over voltages.
- Discharge Voltage: The discharge voltage is the voltage level at which the lightning arrester starts conducting and diverting the surge current. It is typically slightly higher than the system's normal operating voltage.
- Temporary Overvoltage Capability: Lightning arrester transients can cause temporary over voltages in the system. The temporary overvoltage capability of the arrester determines its ability to limit the amplitude and duration of these over voltages.
- Leakage Current: The leakage current is the small amount of current that flows through the lightning arrester under normal operating conditions. A low leakage current is desirable to minimize power losses and prevent unnecessary stress on the arrester.

- Insulation Coordination: Lightning arresters should be properly coordinated with the insulation levels of the protected equipment and the overall electrical system. Insulation coordination ensures that the arrester effectively diverts the surge energy while maintaining the insulation integrity of the system.
- Duty Cycle: The duty cycle refers to the ratio of the time the arrester is subjected to surges (such as lightning strikes) to the total time of operation. The duty cycle affects the arrester's lifespan and performance.
- Environmental Conditions: The operating environment of the lightning arrester, including temperature, humidity, pollution levels, and altitude, can impact its performance and longevity. The arrester should be designed to withstand these conditions and maintain its protective capabilities.

It's important to note that the specific parameters of a lightning arrester can vary depending on its design, application, and the requirements of the electrical system it is intended to protect.

In this study, Zinc Oxide (ZnO) ligthning arrester is chosen due to its ability to operate at high short circuit current. The simulation is done on Benin – Oghara 132KV transmission line of Nigeria power system.

The Benin – Oghara Zinc Oxide (ZnO) ligthning arrester is modelled based on IEEE Surge Protective Device Working Group, and has the following parameters
Maximum Continuous Operating Voltage (MCOV) = 209KV
Height of arrester (d) = 1.8m
Number of parallel columns (n) = 1
L1 (µH) = 42 d/n ; R1 (ohm) = 117 d/n
L0 (µH) = 0.36 d/n ; R0 (ohm) = 180 d/n
C1 (pF) = 100 n/d
For the simulation analysis; the ZnO (A0) and ZnO (A1) characteristics were adjusted to 516kV for a 2kA, 45µs switching surge (Isurge3), and also, the inductor (L1) voltage was adjusted to 604kV for a 10kA 8/20µs lightning surge (Isurge2), then check was done for 10kA 0.5 µs (Isurge1) front of wave 664.5kV versus 665kV from Benin – Oghara

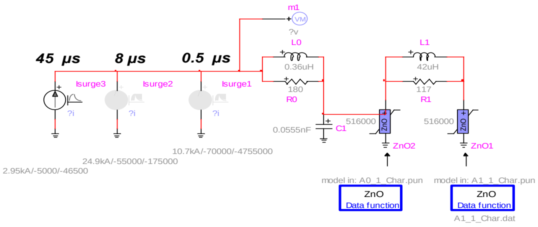


Fig 3: Single line diagram of Zinc Oxide (ZnO) Lightning Arrester on Benin-Oghara 132KV Transmission Line of Nigeria Power System

3. RESULTS AND DISCUSSION

The simulation was carried out in EMTP-RV and Table 1 shows the step variation of the parameters of the ZnO lightning arrester

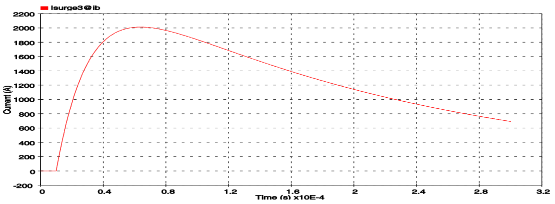


Fig 5: ZnO Arrester: Current–Time Characteristics

The current lightning strike is represented as shown in Figure 5.

Lightning impulses can be modeled as a double exponential of the form:

$$i(t) = IP(e-\alpha t - e-\beta t\ ) = AIPtk\ (e-t/\tau\ ) \qquad (1)$$

Where the constants α and β or *A*, *I.P.*, and τ are chosen to give the required wave shape (rise-time, peak, and duration).

For voltage surges,

$$V_{surge} = \left(\frac{V1}{Ksurge} \times \frac{\left(\frac{t}{\tau 1}\right) surge^{n}}{1 + \left(\frac{t}{\tau 1}\right)\eta surge} \times e - \frac{t}{\tau 2}\right) \qquad (2)$$

And current surge,

$$I_{surge} = \left(\frac{i1}{Ksurge} \times \frac{\left(\frac{t}{\tau 1}\right) surge^{n}}{1 + \left(\frac{t}{\tau 1}\right)\eta surge} \times e - \frac{t}{\tau 2}\right) \qquad (3)$$

Where

$$K_{surge} = e-\tau 1/\tau 2\ ((\eta surge \times \tau 2)/\tau 1\ 1/\eta surge \qquad (4)$$

The parameters for these equations are given in Table 2

TABLE 1: Step variation of ZnO Arrester Parameters

Time (s) x 10E-4	Current (A)	Voltage (V)
0	-200	0
0.4	0	1,000
0.8	200	2,000
1.2	400	3,000
1.6	600	4,000
2	1000	5,000
2.4	1200	6,000
2.8	1400	7,000
3.2	1600	8,000
3.6	1800	9,000
4	2000	10,000
4.4	2200	11,000

Figure 5 shows the plot of short circuit current and each case that the response time of the ZnO lightning arrester is adjusted. As the time increased from 0 to 4ms, the short circuit current increases as well to a point where the increase in turn starts to lead to a decrease.

Tw is the width (time between the 50 percent of the peak when the waveform is rising and falling), *Tvr* is the rise-time for voltage surge (time between 30 and 90 percent level when wave front is rising), *Tir* is the rise-time for the current surge (time between 10 and 90 percent level when wave front is rising), *Td* is the duration (time between the minimum value while rising and the 50 percent level when wave front is falling).

Table 2: Parameters for Surge Equation

Surge	***v*1 or *i*1**	***τ* 1**	***τ* 2**	***ζ surge***	***Tf***	***Td***
1.2/50μs voltage surge	0.94	0.356μs	65.854μs	1.852	1.67×*Tvr*	*Tw*
8/20μs current surge	0.939	47.52μs	4.296μs	2.741	1.25×*Tir*	1.18×*Tw*
10/700μs voltage surge	0.937	2.574μs	945.1μs	1.749	1.67×*Tvr*	*Tw*
5/320μs current surge	0.895	1.355μs	429.1μs	1.556	1.25×*Tir*	*Tw*

The behavior of a zinc oxide (ZnO) arrester is typically represented by a voltage-current characteristic graph rather than a time-current graph; it is not commonly plotted in terms of time in seconds. However, explanation can be given of how the current changes over time during a surge event:

During a surge event such as a lightning strike or switching operation, the current flowing through a zinc oxide arrester will typically exhibit a rapid rise and fall. The rise time and duration of the surge depend on the characteristics of the transient disturbance and the arrester's response time.

Initially, when the surge begins, the arrester is in the leakage region, and only a small leakage current flow through it. As the surge voltage exceeds the arrester's threshold level, the arrester enters the breakdown region and rapidly changes its resistance to become highly conductive.

The current through the arrester increases quickly to its peak value as the surge voltage rises. The arrester effectively clamps the voltage to a certain level, preventing it from propagating further into the protected system. The magnitude of the clamping current depends on the magnitude of the surge and the arrester's characteristics.

Once the surge voltage starts to decrease, the current through the arrester also decreases. The duration of the surge depends on the transient event and the arrester's response time. The arrester's capability to withstand and dissipate the energy of the surge allows it to return to its high resistance state once the surge is over, ready to protect against future events.

It's important to note that the specific time-current characteristics can vary depending on the arrester's design, voltage rating, and the nature of the surge event. Detailed information and specifications for a particular zinc oxide arrester can be obtained from the manufacturer's datasheet or specifications.

4. CONCLUSION

In conclusion, the identified gap of using EMTP-RV to investigate electromagnetic transient in lightning arrester concerning the Benin – Oghara 132KV transmission line was achieved, more so, as previous investigation done was with other simulation tools like;Power Systems Computer Aided Design (P.S.C.A.D.), Electromagnetic Transient Direct Current (E.M.T.D.C.). Using the Electromagnetic Transient Program (E.M.T.P.) philosophy, the control equations are solved separately from the power system equations, thereby maintaining the symmetry of the conductance matrix. The main facilities developed to segment the control, as well as devices or phenomena which cannot be directly modeled by the basic network components, are TACS and MODELS (in the original E.M.T.P. package) and a C.M.S.F. library (in the PSCAD/EMTDC package). The separate solution of control and power system introduces a time-step delay; however, with the sample and hold used in digital control, this is becoming less of an issue. Modern digital controls, with multiple time steps, are more the norm and can be adequately represented in E.M.T. programs.

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