Fault Assessment and Mitigation of the 132kV Transmission Line in Nigeria using Improved Resonant Fault Current Limiting (RFCL) Protection Scheme

D. C. Idoniboyeobu, S. L. Braide, and Wigwe Chioma Elsie

Abstract—This research work proposed an improved Resonant Fault Current Limiting (RFCL) protection scheme to reduce the impact of three-phase short-circuit faults in a power system sub-transmission network. The model used an interpolator-extrapolator technique based on a Resonant Fault Current Limiter (RFCL) for automating the procedure of predicting the required reactor value that must be in resonant circuit to limit the short-circuit current values to permissible values. Using the developed model, short-circuit fault simulations on the three phases of the transmission line (Phase A-C) were performed in the MATLAB-SIMULINK environment. Simulation results were obtained by varying the resonant inductance (reactor) parameter of the RFCL circuit for each of the phases to obtain permissible short-circuit current levels and the values used to program a functional interpolator-extrapolator in MATLAB; the resonant values were typically set to values of inductance equal to 0.001H, 0.01H and from 0.1H to 0.5H in steps of 0.1H. Simulation results revealed the presence of very high short-circuit current levels at low values of the resonant inductor. From the results of simulations, there are indications that the RFCL approach is indeed very vital in the reduction of the short circuit current values during the fault and can safeguard the circuit breaker mechanism in the examined power system sub-transmission system. In addition, lower fault clearing times can be obtained at higher values of inductances; however, the clearance times start to converge at inductance values of 0.1H and above.

Index Terms—Resonant Fault Current Limiters (RFCL); Interpolator-Extrapolator (IE).

I. INTRODUCTION

A. Background of the Research

Design of protection scheme for prompt clearing of fault is critical for Protection Engineers along the Alaoji/Afam Transmission line such that fault clearance within the transmission line is achieved should be achieved at very minimal time interval so to avoid insulation breakdown in the substation [1]. Fault assessment is important however to ascertain the nature and frequency at which faults occur so that a fault mitigation scheme can be implemented for effective delivery of power to end users. The Nigerian 132KV Network from Alaoji to Afam in prone to Phase to ground and Phase to Phase faults. These conditions occur at 70% and 15% frequencies respectively while Two phase to ground, Phase to phase and third phase to ground, all three phases to ground faults and All three phase short-circuited occur at lesser frequencies. It is important therefore to develop a model that can help to clear faults on the transmission network irrespective of their frequencies of occurrence in developing such model for protection of transmission line, emphasis is placed on the ability of the protection scheme to clear all fault conditions before or at the critical clearance time. A transmission line Protection scheme is designed to detect, disconnect or isolate any fault on the transmission line without any delay by the installation of over current protection relays.

B. Aim of the Research

The aim of this Research is to develop a power system model for Fault Assessment and Mitigation of 132kV Transmission Line from Alaoji to Afam in Nigeria.

C. Objectives of the Research

The objectives of this study are as follows:

• To develop a simulation model in the MATLAB/SIMULINK language that can assist in the enhancement of the over current protection on the Alaoji/ Afam transmission line.
• To determine the critical clearance time of a fault and to minimize the fault current flow through the protection devices on the transmission line.
• To develop an improved Resonant Fault Current Limiting (RFCL) protection scheme for adequate and reliability on the transmission line.

II. THEORETICAL REVIEW

Faults are the most common perturbation the power system can be subjected to; and for these variations of faults or fault conditions, Power System Engineers are basically preoccupied with improving system reliability and efficiency by ensuring overall system resilience. Resilience for the electric grid and the key concepts related to system resilience has been investigated [2]. Its aims where to advance system resilience by adding cyber-physical resilience concepts to power systems vocabulary as such, proposed a new way of thinking about grid operation with unexpected extreme disturbances and hazards and leveraging distributed energy resources.

This has become crucial owing to the fact that advanced sensors, intelligent automation, communication networks, and information technologies (IT) have been integrated into the electric grid to enhance its performance and efficiency. Obviously, thinking of fault as the only or perhaps frequently occurring scenario that adversely affects power system operation is limiting as shown by further interconnections through the integration of
intelligent/artificial intelligence that enhances system resilience into the power system. The concept of a power system’s cyber-physical resilience centers on maintaining critical functionality of the system backbone in the presence of unexpected extreme disturbances. Resilience is a multidimensional property of the electric grid; it requires managing disturbances originating from physical component failures, cyber component malfunctions, and human attacks [2].

Improving system resilience for fault mitigation in the power system must also take into cognizance, environmentally induced fault conditions such as wind, rainfall or automobile accidents. These factors could lead to short circuit faults or 3-phase faults on transmission networks and enhancing the reliability and system performance remain the desire of end users as such, the effect of wind on transmission lines and its consequent result in modeling error has been experimented [3]. The study proposed a new method for complete 3D transmission line model construction using inner and across span analysis. The proposed method was modeled for inherent adaptive and capability of indirectly estimating noise scales, which corrupts the quality of laser observations by varying wind speeds through a linear regression analysis. In dealing with fault assessment on transmission networks, correcting partial modeling errors, as well as refining transmission line models is essential at the planning period of the power system.

In dealing with the dynamic nature of faults, the resilience of dynamic operational power grid to cascading failures during real-time in both scalable and robust manner has been of interest [4]. The study examined the problems associated with cascading failures especially in monitoring the resilience of an operational power grid to cascading failures and how they can be prevented using a mitigation plan based on robust metric on the topology and operative state of a power grid to quantify the robustness of the grid. Consequently, a three categorical solutions for mitigating distance protection relay mis-operation which is caused by variations in power flow due to cascading failure has been proposed [5] based on surveys with a focus on anticipatory distance relay protection mis-operation, communication assisted protection and a modifiable local distance protection scheme. A three solution approaches were adopted in solving the problem of zone 3 distance protection mis-operation with ranges from the anticipation and prevention of mis-operation in the planning stage, communication assisted protection schemes that use remote measurements to enhance relay security and the use of local data at both ends to enhance distance relay security.

There is probably no fault free system [1] as such, mitigation models in the event of faults are incorporated in power system design to avoid insulation breakdown due to short circuit current [6]. A mitigation model is usually proposed without limitation to any particular fault but in consideration of the wider spectrum, such that the model should be adaptive to either Symmetrical or Asymmetrical faults etc.

A. Models for Fault Mitigation

Several methods of fault mitigation have been proposed by researchers and Engineers, in an attempt to present the most effective model, but these methods are only relative to the power system in consideration. In some cases, simulations were performed for the quantification of severe weather events and its impact on the reliability/availability of power grid infrastructures [7] while the use of fault chains have also been investigated in relation to the resilience of power systems [8]; the idea was to segment a class of fault events into an initial and middle segments so that faulted segments can be isolated. Similarly, fast gossip algorithms have been used to solve problems related to cascading failures in a power system [4] as well as Dynamic Line Rating (DLR) algorithms for over current protection in transmission lines [9]. A-two mitigation strategies were also proposed using the principle of optimal power flow (OPF) for real-time cyber-physical power systems to analyze the impact of failures in power system [10] such was adapted in a preventive re-dispatch of generators to ensure a predefined minimum critical time for faults at all buses of the IEEE 118-bus test system [11].

Developing a preventive algorithm for fault assessment may not be feasible for all cases as such, a fragility model of a power systems transmission network for real-time assessment of severe weather events (winds) on the power network was equally proposed [12]. In line with the assessments, a probabilistic multi-temporal and multiregional resilience assessment methodology using the optimal flow and a sequential Monte Carlo simulation for impact assessment of a wind storm on the Great Britain power system was established. Consequently, the effects of severe over-voltages on interconnected sub-network of the BC Hydro with the single-phase trip and recluse scheme was investigated. Mitigation measures using a dynamic enable/disable single-phase trip scheme was adopted [13] while a protection scheme for tackling the AC breaker inaction problem holds greater efficiency in the presence of line faults on a hybrid AC/DC power transmission system [14]. A synchronphasors have been used to detect and mitigate origin and progression of oscillations in the grid. This involves the use of Phasor Measurement Unit (PMU) data that can help system operators observe discrepancies in the grid [15]. A Line Outage Distribution Factor (LODF) and a Power Transfer Distribution Factor (PTDF) has been proposed to determine the most efficient demand-side action within a localized setting. By building in scenario data, a power system operator can take advantage of PTDF and LODF to determine the likelihood of a line fault and avert future line outages under extreme weather or local line flow events [16].

B. Research Gap

A concerted research effort was taken during the course of this work as seen from the extensive review of existing and relevant works, to explore what is available in the body of knowledge as it relates to fault assessment and mitigation in the Power System, but particularly in the Alaoji - Afam 132 kV Transmission Line. This extensive review was affirmative of the keen interest in fault mitigation and assessments with several models proposed, but none was explicitly recommended for the Alaoji - Afam 132 kV
Transmission, hence the need to fill this research gap by proposing an improved Resonant Fault Current Limiting (RFCL) protection scheme for the Alaoji - Afam 132 kV Transmission Line.

III. METHODOLOGY

Protection devices such as over-current relays and circuit breakers play very important and vital role in protecting both the lines and sensitive equipment during a fault condition. However, these devices are prone to failure when their rated current/voltage capacities are exceeded hence current-limiting becomes necessary.

The materials and methods that can assist power system protection engineers assess the magnitude of the fault current and the application of appropriate mitigation measures based on Resonant Fault Current Limiter (RFCL) is discussed. The technique proposed will enable power protection engineers and specialist gain better understanding on the influence of associated system parameters for a better and reliable operation of the power system protection devices.

A. The Alaoji 132KV Transmission Line implemented in Simulink

The transmission line model used in this study is a 25 km, 132 kV double-circuit transmission line with the necessary power system protective components and signaling devices such as the circuit breakers and current transformers. The network has been modeled using MATLAB Simulink Language as shown in Fig. 1 below and a fault current limiter has been incorporated to avert the disastrous over-current situation that occurs in a short-circuit fault on the line. All necessary measurement and indication devices such as the voltage and current measurement, multimeters and signal displays have been incorporated as well. Resonant Fault Current Limiting (RFCL) is added to further improve the resilience of the power system protection circuit. The RFCL system includes the resonant capacitor, thyristor, surge arrestor, logic comparison circuit and the current limiting reactor. It is important to note that the capacitor and the current limiting reactor form a resonating line that permits free-flow of current during a normal (short-circuit-free) operation. In an abnormal (faulted) situation, the resonating path is bypassed to include only the current through the reactor using the thyristor as a switching link.

![Fig. 1 Fault Detection and Mitigation Model adapted to the TL](image)

Table I below gives the initial parameters for the RFCL used in the proposed model. Varying these parameters (capacitance and inductance values) should give an indication of the limits including best and worst operating points of the protective system during faulted events.

<table>
<thead>
<tr>
<th>Component</th>
<th>Set Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance</td>
<td>0.3H</td>
</tr>
<tr>
<td>Capacitor</td>
<td>100µF</td>
</tr>
</tbody>
</table>

B. Fault Level Detection and Mitigation Methodology

In order to determine the magnitude of the short-circuit fault and proffer appropriate mitigation strategies, it is important to define some set of rules or procedure as depicted in the flowchart of Fig. 2.

DOI: [http://dx.doi.org/10.24018/ejers.2018.3.10.796](http://dx.doi.org/10.24018/ejers.2018.3.10.796)
C. The RFCL using Interpolator-Extrapolator Technique

A scheme of an Interpolator-Extrapolator (IE) technique is as shown in Fig. 3. The primary purpose of the Interpolator-Extrapolator is to function-fit a monotonically increasing input (x-dataset) to a corresponding target (y-dataset). If the data is non-negative and shows a trend, then the Interpolator-Extrapolator is a very efficient and fast technique for function-fitting when compared to popular techniques such as neural networks, fuzzy logic or regression. Fast in the sense that it employs an approximation procedure based on a Look-Up Table (LUT). A detailed scheme of the IE technique including the necessary sub-system control logics employed in this work has been developed in the MATLAB/SIMULINK language and is provided in the Appendix.

IV. RESULTS AND DISCUSSION

One of the benefits of a fault protection device such as the over-current relay or circuit breaker is that it provides a means of preventing the failure of sensitive power transmission line components such as the transformers and transmission lines. However, this very important feature is lost when short-circuit current carrying capacities of these protective devices are exceeded. Thus, fault current limiting circuit becomes necessary in order to guarantee the security of the power transmission system.

A. Simulation Procedure for Fault detection and mitigation using RFCL

The simulation for fault detection and mitigation based on the RFCL is based on the transmission line presented in the Simulink model of Fig. 1 were performed not by estimating the parameters of the RFCL as previously done [17], but by varying the component parameters and the short circuit current level so that the critical fault-clearing time can be estimated. The procedure for fault detection is presented first, and then the appropriate mitigation is presented next. Fault detection therefore involved the following two processes:
1) Indication

Indicators are incorporated to alert the system operator, when a fault occurs. Specific techniques used include alarms, indication lights and sirens. Also, remote messaging from fault point to operator detection rooms or gadgets indicating the presence of a fault along the transmission lines may also be employed.

2) Measurement

Measurement technique are employed to determine the level of fault through the short-circuit current that flows through protective equipments and the line of course. The magnitude of the fault current should then guide power system protection engineers on the right rating of power protection devices in addition to the amount of current-limiting that must be applied to protect the protection devices themselves.

B. System Results under Normal Conditions

Simulation results are presented in Table II for varying inductance (L) between 0 and 1 and the short circuit current (I_sc) level read and recorded.

<table>
<thead>
<tr>
<th>Inductance (H)</th>
<th>I_sc (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>27.46</td>
</tr>
<tr>
<td>0.2</td>
<td>14.44</td>
</tr>
<tr>
<td>0.3</td>
<td>08.44</td>
</tr>
<tr>
<td>0.4</td>
<td>05.94</td>
</tr>
<tr>
<td>0.5</td>
<td>04.58</td>
</tr>
</tbody>
</table>

C. System Results under Normal Conditions

Simulation results are presented in Table III for varying inductance (L) between 0 and 1; the short circuit current level and fault-clearing time (t_c) are read and recorded for phase A to ground faults. Further simulation results of tests conducted considering a range of inductance from 0.1H to 0.5H at intervals of 0.1H are presented in the accompanying sub-sections.

<table>
<thead>
<tr>
<th>Inductance (H)</th>
<th>I_sc (A)</th>
<th>t_c (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.002</td>
<td>81400</td>
<td>21.7</td>
</tr>
<tr>
<td>0.010</td>
<td>33700</td>
<td>20.4</td>
</tr>
<tr>
<td>0.100</td>
<td>3402</td>
<td>16.7</td>
</tr>
<tr>
<td>0.200</td>
<td>1535</td>
<td>16.7</td>
</tr>
<tr>
<td>0.300</td>
<td>966</td>
<td>16.7</td>
</tr>
<tr>
<td>0.400</td>
<td>699</td>
<td>16.7</td>
</tr>
<tr>
<td>0.500</td>
<td>545</td>
<td>16.7</td>
</tr>
</tbody>
</table>

D. Discussion of System Results under Faulted conditions for Phase A: Inductance Range 0.1-0.5H

Simulations were performed by setting three-phase fault block to Phase-A with ground connection while all other phases were disconnected. The result of breaker voltages and currents for phase A at L=0.1H is presented below. Simulations for L=(0.2-0.5)H equally show similar result pattern.

From the simulation result for phase A at L=0.1H, a very high short circuit fault current was obtained, but as the inductance is varied by increasing the value, the value of the short circuit fault current began to recede. This pattern was consistent for higher range of inductance values This procedure was repeated by carrying out simulations for L=(0.2-0.5)H as reported with L=0.5H generating the least fault current on comparative basis. This is indicative of an inverse relationship between the short circuit fault current and the Resonant Fault Current Limiter introduced in the research for fault mitigation. It implies therefore that fault assessment and mitigation can be effectively achieved by raising the value of the inductor adapted in the transmission line as presented earlier.

E. Discussion of System Results under Faulted conditions for Phase B: Inductance Range 0.1-0.5H

Simulations for Phase-B faults are performed in a similar manner as Phase-A.

The results of the breaker voltages and currents for phase B at L=0.1H is presented for discussion while the system response for L=(0.2-0.5)H was also studied. Phase B exhibited very high fault current, but significantly lower than phase A, when subjected to the same operational condition. The fault current also receded as the inductance value is raised gradually until L=0.5H in conformity with the previously studied condition on Phase A.

F. Discussion of System Results under Faulted conditions for Phase C: Inductance Range 0.1H-0.5H

Simulations for Phase-C faults are performed in a similar manner as Phase-A. The results of the breaker voltages and currents presented below for discussion.
At Inductance value of 0.1H, phase C exhibited high fault current but significantly lower than phase A and B and by increasing the inductance value to 0.5 as reported, a much better system response for fault limiter was obtained. Although such better system response was obtained much earlier at phase A at L=0.4H as indicated. Phase C also conformed with the inverse relationship approach introduced by the RFCL circuit introduced for fault assessment and mitigation when subjected to similar fault condition as earlier seen in Phase A and B.

G. Comparative Discussion

From the results of simulations conducted Phase by Phase and circuit-by-circuit, it is obvious that the inductance has a strong influence on the Short-Circuit current limit capability of the RFCL. For Phase-A to C faults it is possible to achieve a fault limit of up to 1000A. However, during Phase-A faults much lower fault limit is achieved much earlier than Phase-B and Phase-C. This can further be evaluated by comparing the sinusoidal waveforms for phase A at varying inductance as well as phase B and C also at varying inductance. Phase-A also exhibited the highest fault limit at an inductance value of 0.1 when compared with Phase B and C at same inductance value, but its fault current was limited much earlier than phase B and C.

V. CONCLUSION

Fault mitigation in the context of electrical power systems have been discussed in this research study and an enhanced technique based on a resonant fault current limiting (RFCL) interpolator-extrapolator proposed. The system has been modeled in the MATLAB/SIMULINK language and simulation results generated to validate the proposals. The results demonstrate that it is indeed possible to reduce the fault current by increase of the inductance values to the RFCL. However, for practical reasons, there might be oscillations at particular values of inductance limiting the extent to which the inductance can be increased.

VI. CONTRIBUTION TO KNOWLEDGE

This research has introduced a novel approach to the application of Resonant Fault Current Limiters (RFCL) for the mitigation of three-phase faults in the Alaoji-Afam sub-transmission network based on an Interpolator-Extrapolator (IE) technique and considering fault over-currents. The research specifically introduced a simulation model to facilitate the study of the aforementioned network using the MATLAB/SIMULINK environment. To the best of the author’s knowledge, this is the first attempt at simulating the automated use of RFCL for mitigating the effect of three-phase faults on a power system transmission line in the manner and scheme as presented in this research. Thus, this research work should open opportunities for exploring new automated techniques in power systems protection and control. The resulting simulations show that fault current as high as 200kA is attainable when no fault limit protection scheme is used in the power network which is very dangerous. Using the Resonant Fault Current Limit (RFCL) system will lead to the enhancement of the overcurrent values to as low as 5kA when the resonant inductance is set at a minimum of 0.1H and 1kA when the resonant inductance is set at a maximum of 0.5H. The switching relays (breakers) are also cleared much earlier for Phase A than for Phase B at critical clearance values of 0.02s and 0.025s for Phase A and Phase B respectively.

VII. RECOMMENDATIONS

The research has extended the applicability of RFCLs for power system fault assessment and mitigation by providing a scheme that lends itself to automation. Future work should be directed towards:

i. Dynamic/real-time simulations in a real industry setting.

ii. Validating the effectiveness of the proposed system in other power network domains.

APPENDIX

Sub-System Control

REFERENCES


DOI: http://dx.doi.org/10.24018/ejers.2018.3.10.796


