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DEVELOPMENT OF A GUIDE FOR SAG STUDIES ON POWER LINES USING SIMULATION AND EXPERIMENTAL RIGS

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Abstract

For the effective operations of industrial and domestic systems, power in the right quality and quantity has to be supplied. But this is not always possible due to disturbances on transmission and distribution lines. These disturbances if not properly checked could lead to great losses to both lives and properties. This research focuses on the development and simulation of experimental guide to study sag on power lines. Voltage sag is the sudden drop in the rms supply voltage to between 0.1 to 0.9 pu, it can be caused by the switching ON of heavy loads with high start-up current or as a result of faults on transmission and distribution lines. Various techniques have been proposed for its mitigation ranging from the use of D-STATCOM (Distribution Static Compensator), tap changers, Ferro resonant transformers to the use of DVR (Dynamic Voltage Restorer) which is the most popular technique. In this work, the Federal Polytechnic Bauchi campus was modeled as load centre using Matlab/Simulink where single phase and three phase faults were simulated respectively, over-current protection scheme was also simulated using OCR (Over Current Relay) on the transmission/distribution lines. The effects of starting an induction motor was experimented in the school's Electrical Power laboratory to check for the occurrence of voltage sag. At the end of this research, simulated and experimental results were obtained showing the existence of the sagging problem in power systems and proposed the effective means of tackling it.

Keywords: *Sag, D-STATCOM, DVR, OCR, Power Lines.*

Introduction

Modern industrial machines and intelligent electronic systems demand the supply of un-interruptible, high quality power to operate satisfactorily, and failure to supply this kind of power could be of great loss (both in terms of money and time) to the consumers. The consumers of power require supplies at different level of reliability and security and hence some took pains to improve their power quality with power electronics devices while others need some sort of premium power supply to be available at the required quantity and quality. Thus, increase in the usage of machines with high startup current in the industrial and technological worlds have led to the generation of disturbances on the power lines hence causing low power quality at the customer end. One of such disturbances is voltage sag which has been considered as one of the most harmful power quality problems because they endanger end-user equipment Caicedo *et al* (2012). These disturbances, among other common phenomena like harmonics, voltage swells, interruption etc if not checked could lead to damage of power plant components, erroneous motion of robotics, loss of information on volatile memory, burning of motor coils.. So the study of these disturbances particularly voltage sags is of great importance to both the utility company and the customers at large.

Voltage sag amongst other disturbances is a short-duration reduction in the rms voltage caused by events such as power system faults, load variations and the start of induction motors, Bollen (2000) in Joaquin *et al.* (2012).

Most of the problems of equipment failure, software and data corruption as well as malfunctioning of machines are the results of poor power quality supplied to the consumers.

Voltage sags are mostly caused by either equipment fault or the sudden switching ON of heavy loads with high start-up currents where the rms value of the voltage falls to between 0.1 to 0.9 pu and lasts for a duration of 0.5 cycles to 1 minutes. Unfortunately, it is not feasible to stop the switching of heavy loads or prevent equipment faults in power systems and as such the problems of voltage sags will continue to remain as a disturbance and can only be managed. Thus it becomes very imperative to study this problem in order to understand the level of destruction it can cause to normal operation of power systems.

This research is aimed at developing a guide for sag studies on power lines using simulation and experimental rigs.

The objectives of this work include the following:

1. To simulate fault in a transmission line supplying domestic consumers using MATLAB/Simulink.
2. To simulate an over current protective scheme using MATLAB/Simulink
3. To simulate induction motor starting characteristics for industrial consumers using MATLAB/Simulink;
4. To validate experimentally the effects of switching of induction motors in distribution systems.

Literature Review

Various techniques have been proposed for the mitigation of voltage sag ranging from the use of D-STATCOM (Distribution Static Compensator), solid state tap changers with GTOs (Gate Turn Off), Ferro resonant transformers, to the use of DVR (Dynamic Voltage Restorer) which is the most popular technique. Financial analysis of the impacts of voltage sag on industrial customers has also been carried out.

The business activities of the majority of industrial and commercial customers were found to be dependent on some critical equipment that is susceptible to voltage sag events. Yasir *et al.* (2012) proposed a novel approach to estimate the financial impacts of voltage sag events on businesses more specifically for semiconductor industry using tree diagram and found out that there was a critical financial loss of $1,400,000 (i.e. ₦504,000,000).

An analysis of the fault impedance impact on studies of voltage sags caused by system faults was performed by simulation of 62 case studies of phase-to-ground faults on 13.8, 69, 138 and 230 kV transmission lines and that the number of voltage sags on a power system does not necessarily follow systematic rules Ramos *et al.*(2015).

Loveswara et. al, (2017) proposed a solid state tap changer that uses GTOs. A GTO was preferred over IGBT for their low cost application and higher power applications whenever required. The whole set up was known as an Automatic Voltage Regulator, it was a very fast and effective system for sag mitigation but could be susceptible to high transients due to its poor transient rejection and complexity.

In a research carried out by Noronha and Karapurkar (2017), the AC inverter-based regulator and direct AC-AC converters were proposed. The series-connected devices (SD) are voltage-source inverter-based regulators and they compensate voltage sags by injecting the missing voltage in series with the grid. The key features related to the evaluation of certain SD topologies are cost, complexity and compensation ability which is slow.

Amoo (2017) reported the incidence of voltage sags during Olympic game as shown in Figure 1. Figure 6 elucidates more on the concept of voltage sag in distribution systems. Hence, there may be need to understand the responses of the sensitive loads before the deployment of mitigation scheme as precautionary measures.

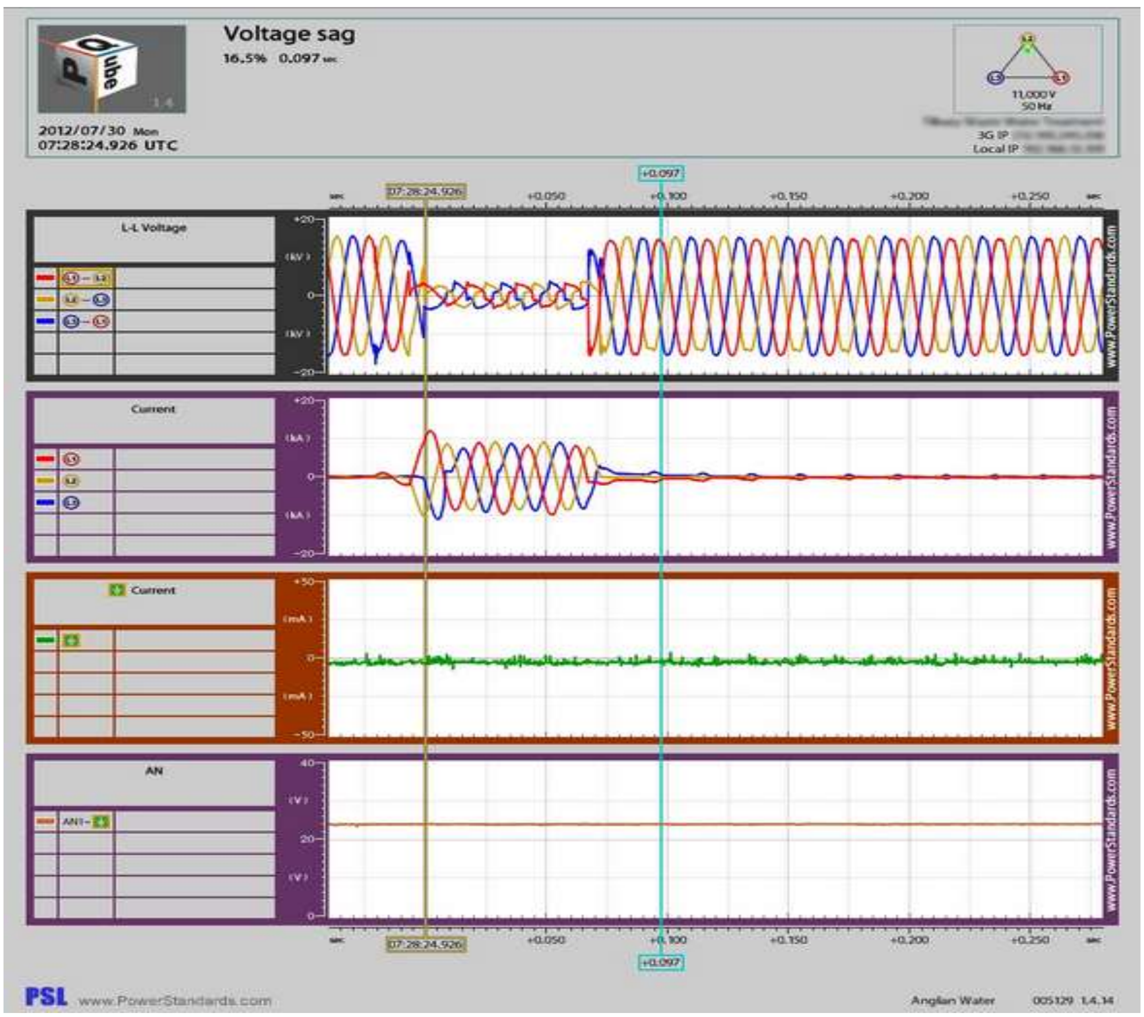

Figure 1: Olympic PQ Waveforms, Amoo (2017)

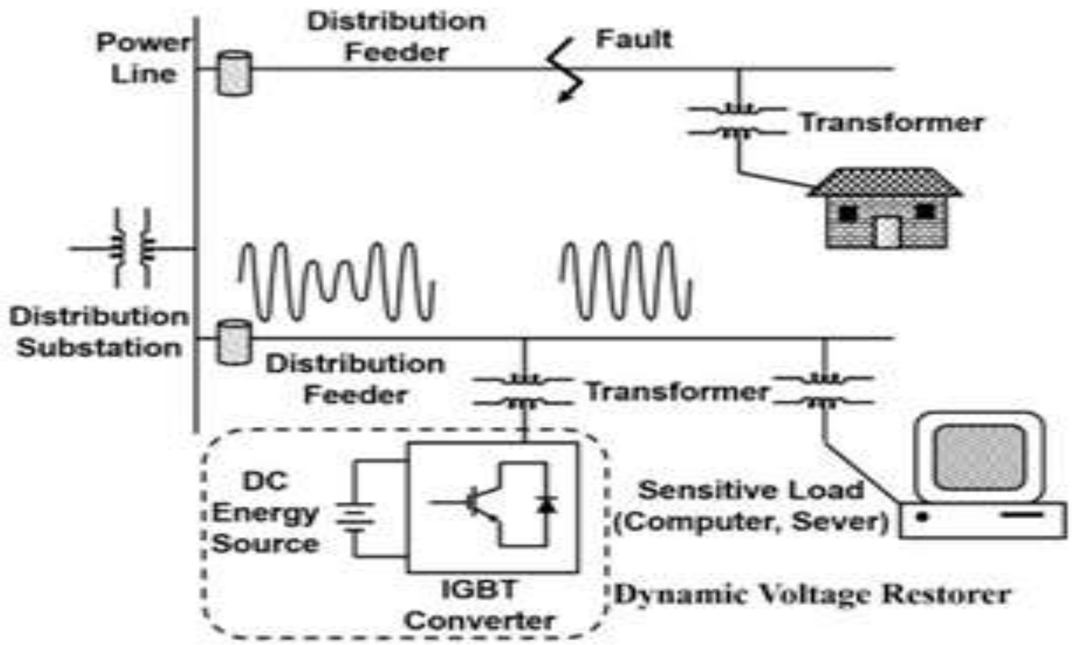

Figure 2: Concept of Voltage Sag, Baliga (2015)

Materials and Methods

Materials

The materials used for this work can be divided into two as shown in Table 1.

Table 1: Materials

Simulation Modules	Experimental Rigs
Personal Computer	**Synchronous Machine Module**
MATLAB/Simulink	**Variable Power Supply**
	Power Quality and Energy Analyzer Fluke 435

Table 2: Synchronous Machine Specification

Model Parts	Parameters
Manufacturer	Electron S.R.L ITALY
Model	Synchronous Machine A4223M
Power	kW 1 kVA
Speed	3000 rpm
Voltage	220/380
Current	2.9/1.
Voltage Nom.	220V
Current Nom.	0.4 A
Production Year	2013

Figure 3: Synchronous Motor module

Figure 4: Variable Power Supply   Figure 5: Power Quality and Energy Analyzer Fluke 435

Table 3: Variable Power Supply Specifications

Model Variables	Parameters	Parameters
Input voltage	**230/400V 3 phase + N +GND 50Hz**	
Output voltage	**(+/- 5%) 3 phase 0 – 430V 5A**	**230/430V 10A**
	1 phase 0 – 240V 5A	**220V 10A**
	DC 0 -240V 10A	**DC 0-220V 1A**
Manufacturer	**Electron S.R.L ITALY**	
Model	**Power Supply A4-A0245 (A0240)**	
Production year	**2013**	

Table 4: Voltage inputs Characteristics of the PQ Analyzer

Characteristics	Parameters
Number of inputs	4 (3 phases + neutral) dc coupled
Maximum input voltage	1000 Vrms
Nominal Voltage range Selectable	1 V to 1000 V according IEC61000-4-30
Maximum peak measurement voltage	6 kV (Transients mode only)
Input impedance	4 MΩ // 5 Pf
Bandwidth	> 10 kHz, up to 100kHz for Transients mode
Scaling	1:1, 10:1, 100:1, 1,000:1, 10,000:1 and variable

Table 5: Current inputs Characteristics of the PQ Analyzer

Characteristics	Parameters
Number of inputs	4 (3 phases + neutral) dc or ac coupled
Type	Clamp on current transformer with mV output or i430flex-TF
Nominal input Range	0 - ± 3.0 Vpeak, 0 - 3.97 Vrms sine wave (selection x1, AC+DC coupled)
0 - ± 0.3 Vpeak	0 – 0.397 Vrms sine wave (selection x10, AC coupled)
Range	0.5 A rms to 600 Arms with included i430flex-TF (with sensitivity 10x)

Signals	DC components are blocked.
Input impedance	1 MΩ
Bandwidth	>10 kHz
Scaling	1:1, 10:1, 100:1, 1,000:1 10,000:1 and variable

Methods

The flowchart of Fig.6 presents the implementation process of the work.

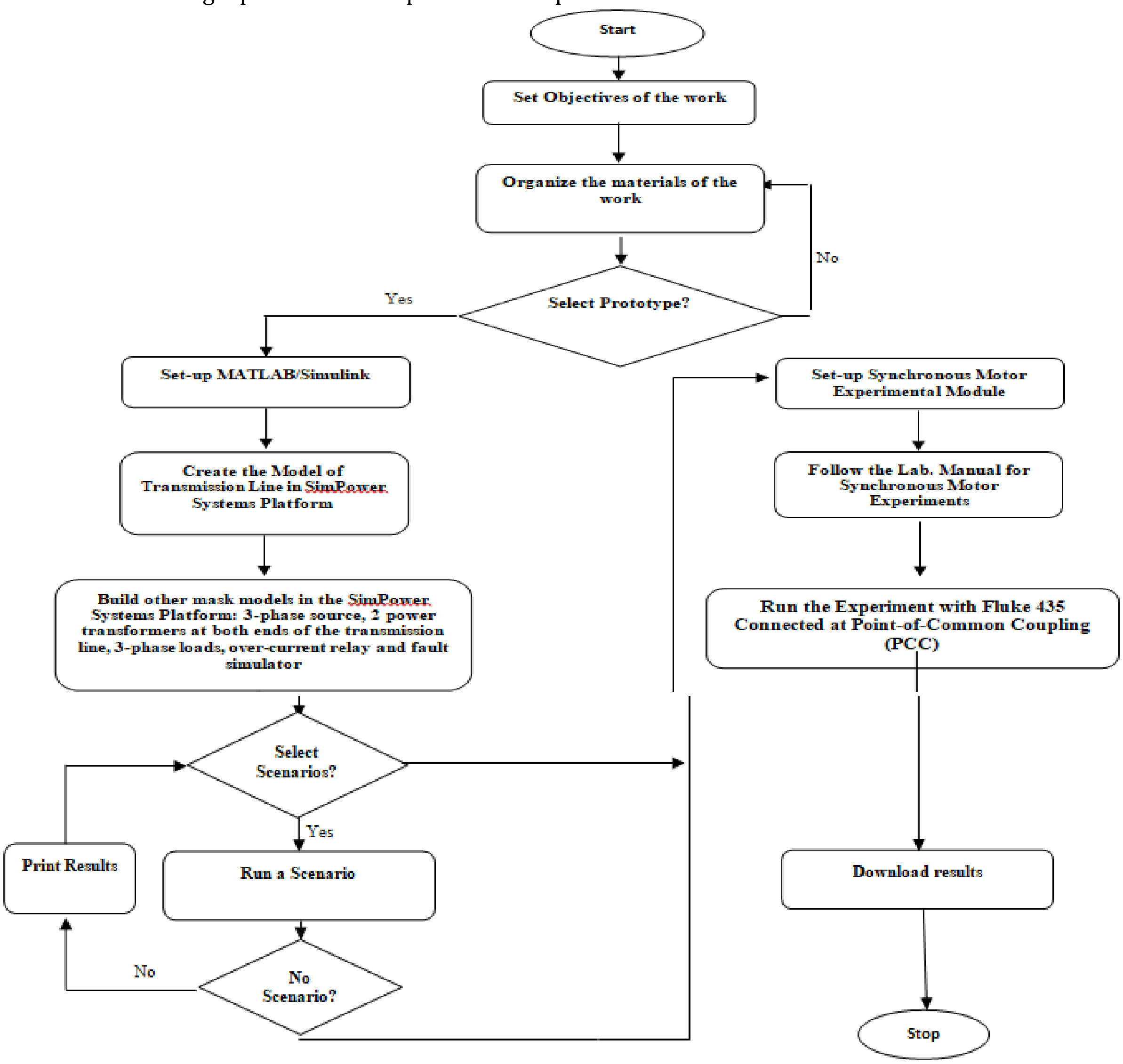

Figure 6: Flowchart showing the Implementation Process

Experimentation on Synchronous Motor

In the Electrical Power laboratory, a variable power supply, synchronous motor with circuit breaker and PQ analyzer for measurement of PQ events were connected as shown in Figure 2.

This is the experimental set-up to study the inception of voltage sag caused during the operation of an electric motor.

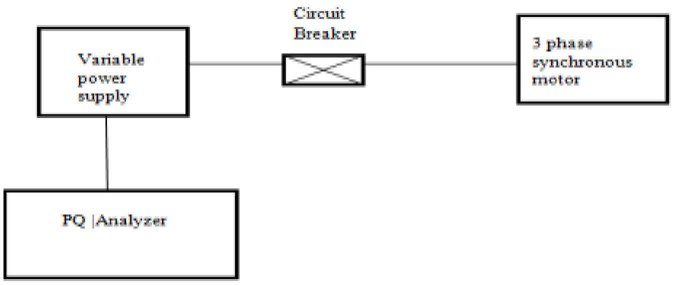

Figure 7*: 3-phase synchronous motor connected to Mains power supply*

4.0 Results and Discussion

Experimental results are presented first followed by Simulation results.

Experimental Results

The voltage sag captured during the operations of the motor are shown in Plates V and VI. Plate V shows result of the voltage waveforms before the connection of the motor. The RMS voltages as displayed on the meter are; L1, L2 L3 and Neutral are 200.3V, 187.1V, 209 V and 11V respectively for scenario when there was no voltage sag. On the other hand, Plate VI shows the situation when the motor was connected such that the voltage sag apparently displayed the RMS of the 3-phase as L1, L2 L3 and Neutral are 198.2V, 181.4V, 214.2V and 14 V respectively. However, at the time 44s when the motor was running the voltage sag was momentarily observed in all the lines. This is fault inception when the magnetic field of stator winding is ongoing instanteneously changes and needs a finite time to stabilize.

Figure 8: Result on Power Quality Analyzer on normal condition

Figure 9: Result on Power Quality Analyzer on sag condition

Simulation results

Figure 4 shows the MATLAB simulation of a standard 25 kV test transmission network with a no fault condition hence, no occurrence of voltage sag. Figures 5 and 6 show the simulation of a 25 kV transmission network with fault conditions, it consists of a grid supply, two transformers located 80 km apart between the sending and receiving ends respectively. It also has a circuit breaker, three phase load, fault simulator and scopes connected to monitor the signal waveforms. Two scenarios were considered: single and 3-phase faults. Figure 5 shows a case where three phase fault was activated while Figure 6 shows the case of a single line to ground fault activated which affected only line L_3, the other lines L_1 and L_2 are normal. The duration for the voltage sag was set between 0.5 and 0.8 seconds in the scenarios considered. The magnitude of the voltage during the sag conditions were observed to nearly drop to zero volt. After the span of 15 cycles (i.e. 25 cycles to 40 cycles), the network recovered from its low voltage and the magnitude of the bus voltage approaches the nominal value of 20 kV peak. Figure 7 shows the setting of the transformer parameters.

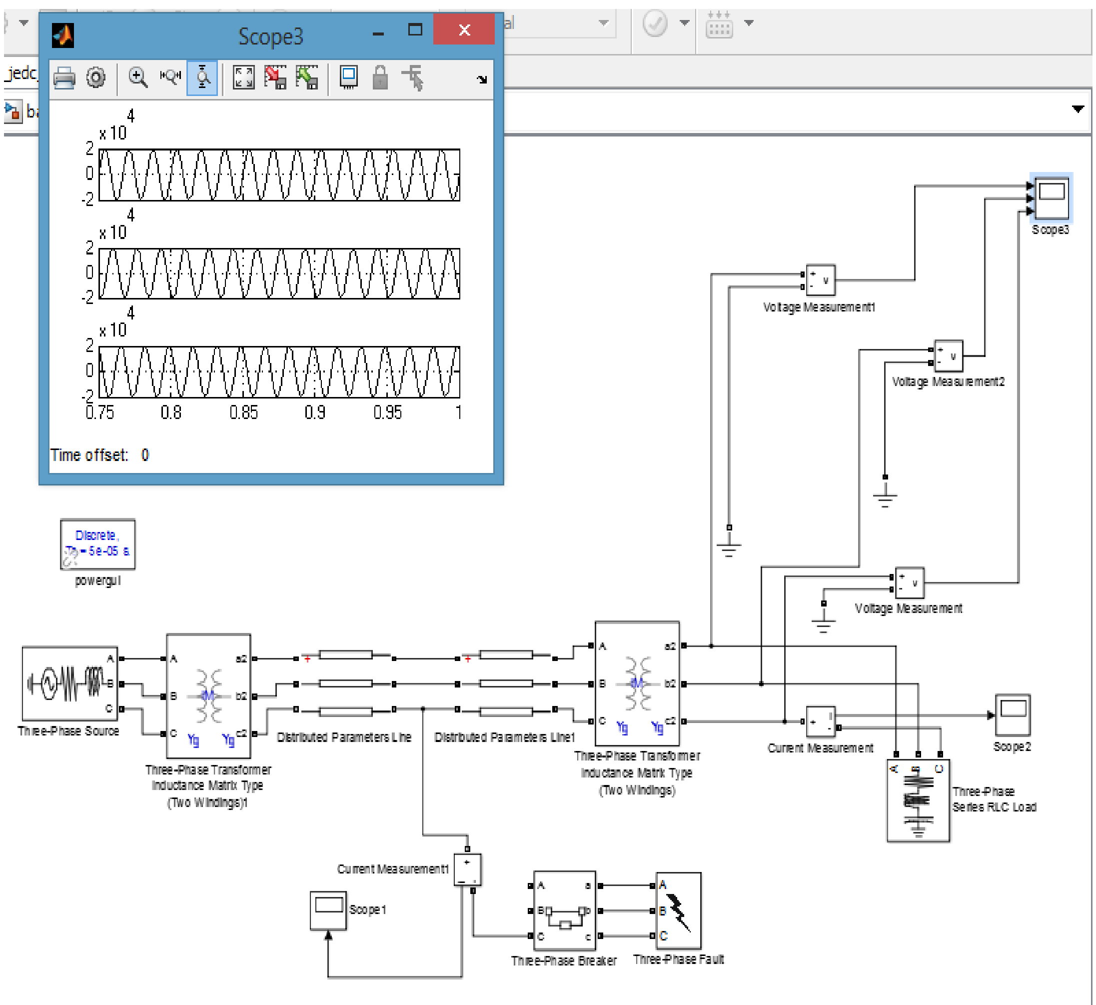

Figure 10: MATLAB/Simulink Result of a 25 kV Transmission Network under no Fault Condition.

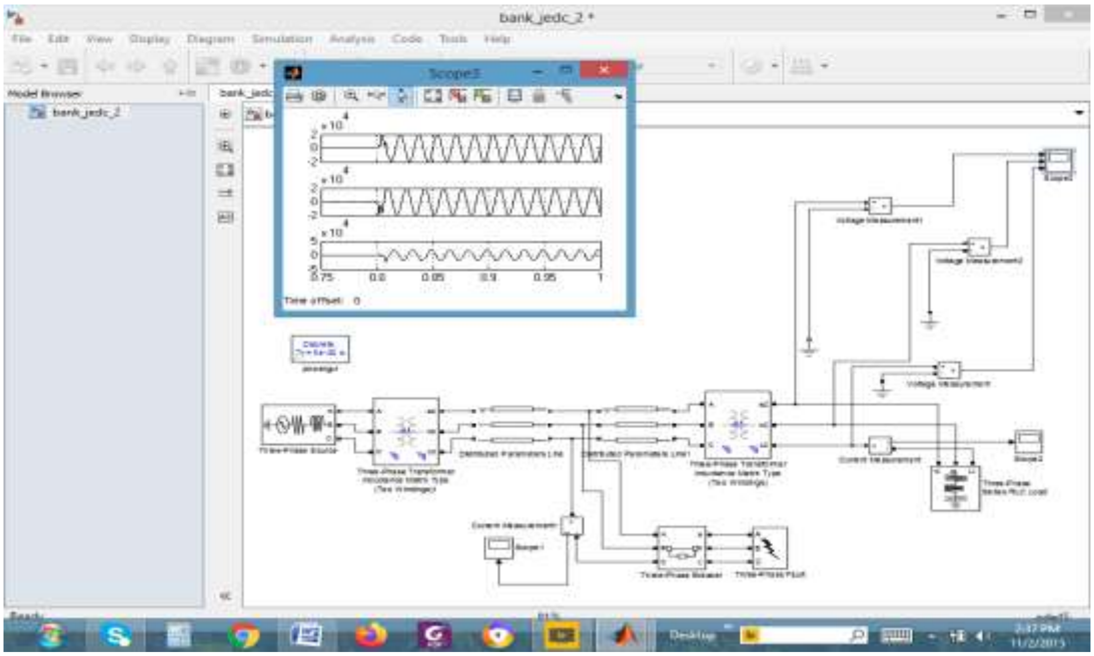

Figure 11: MATLAB/Simulink Result of a 25 kV Transmission Network under Fault Condition due to Voltage Sag caused by L-L-L G Fault Current with 2x40 km Transmission Line

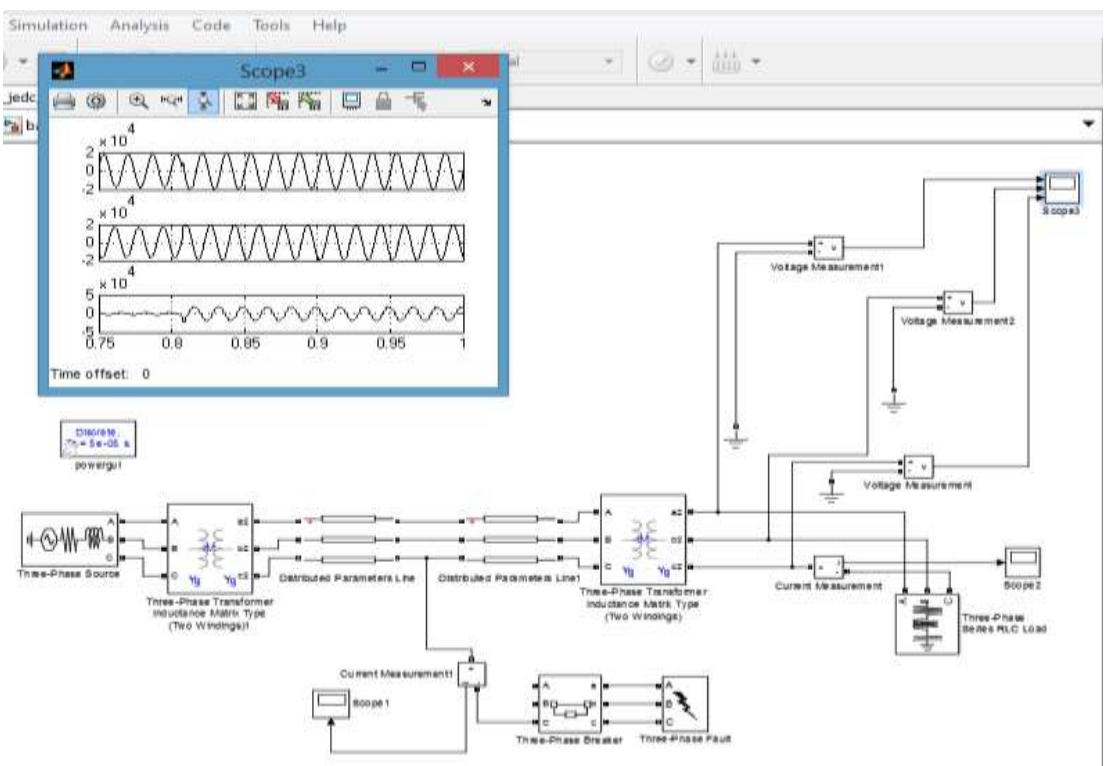

Figure 12: MATLAB/Simulink Result of a 25 kV Transmission Network under Fault Condition due to Voltage Sag caused by L- G Fault Current with 2x40 km Transmission Line

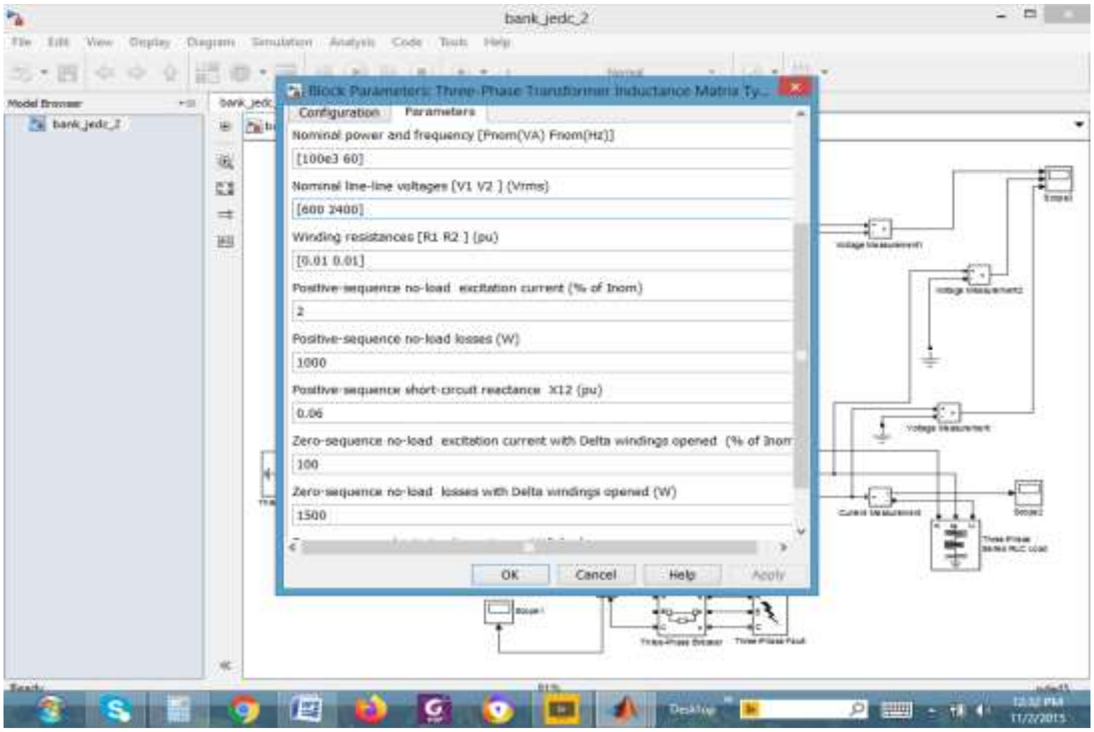

Figure 13: Setting of Transformer parameters for MATLAB/Simulink of a 25 kV Transmission Network under Fault Condition due to Voltage Sag caused by L- G Fault Current with 2x40 km Transmission Line

Conclusion

One of the major problems of power quality is voltage sags and the study of this problem could reduce financial losses to both the utility company and the customers at large. This work explored voltage sag as a power quality problem. Voltage sag can be caused by the starting of large motors with high startup current, faults on transmission and distribution lines and even voltage variation. It can lead to equipment failure, software and data loss and corruption as well as malfunctioning of machines. Experimental and simulation results using MATLAB/SIMULINK in this research have proven the existence of this problem which is inevitable. There are several mitigation techniques but the most suitable method would have to depend on a proper understanding of this problem.

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