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OPTIMIZING THE POWER FACTOR OF DISTRIBUTING TRANSFOMER USING SHUNT CAPACITOR BANK

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ABSTRACT

This study focuses on optimizing the power factor of distribution transformers through the implementation of a shunt capacitor bank. By sizing and deploying the capacitor bank at the secondary side of the transformer, the system was effectively enhanced. Simulation conducted via Simulink revealed a notable improvement, with the power factor reaching 0.987 (pu). Comparative analysis between the transformer with the shunt capacitor bank and its characterized counterpart showcased a significant 6.3% enhancement in performance.

1. INTRODUCTION

Today, the reliability of power transformers has been significantly affected by various issues, including overloads, inadequate maintenance, and high loss rates. Consequently, the quality of power distribution has been compromised, posing a persistent challenge over the years. While the straightforward solution might be to replace these transformers, the high cost involved renders this option impractical.

As highlighted by Amoiralis et al. (2009), transformers serve as essential electrical machines facilitating the transmission and distribution of electrical energy. They play a pivotal role in interconnecting power systems at different voltage levels, enabling the utilization of electric power in numerous applications. Therefore, transformers occupy crucial positions within the electric power system, serving as vital links between power generating stations and points of electric power utilization. They are responsible for converting voltage and current from one level to another, while maintaining a constant output regardless of the input within a certain range.

Solid-state transformers (SSTs), developed with thyristor-based AC to AC converters, offer the potential for additional benefits compared to traditional transformers in terms of power quality and controllability. These benefits include improved regulation of power, output voltage control, reactive power compensation, voltage regulation (flicker compensation), and power factor correction (Al-Hafri et al., 2016). However, challenges such as slow switching and low power ratings of semiconductors have hindered the widespread implementation of SSTs in power systems during this era (She et al., 2013; Krishnamothy et al., 2018).

Dieter (2013) proposed the use of on-load tap changers for transformer control and voltage stability. However, conventional tap changers are plagued by mechanical complexities involving gear mechanisms of selectors, diverters, and switches. To enhance power supply quality and optimize power system device operation, shunt banks have been introduced. These banks are installed to compensate for capacitive reactance and correct power factor. In this work, we employ shunt capacitor banks to address the nonlinear magnetic flux density experienced in power saturation transformers. The aim of this paper is to optimize the power factor of power transformers through the intelligent deployment of shunt capacitor banks. The objectives are to develop a model that enhances the power factor of transformers using shunt capacitor banks, implement the developed model on Simulink, and evaluate its performance.

2. LITERATURE REVIEW

The review examines various studies on transformer design and optimization, focusing on different techniques and their applications. Amoiralis (2009) conducted a literature survey, presenting several optimization techniques without recommending a specific one as superior. Georgilakis (2009) advocated for solid-state transformers, emphasizing their benefits for automatic voltage regulation, although their implementation cost was noted as a limitation. Williams et al. (2015) explored the impact of solid-state electronics on power system control, with a focus beyond transformers specifically. Rabih (2015) applied geometric programming to transformer design, though its implementation complexity was noted. Judd and Kressle (2017) discussed the design optimization of low-frequency power transformers with on-load tap changers, emphasizing the need for voltage control and regulation of these devices.

3. DATA COLLECTION

The data was collected from the Enugu Electricity Distribution Company (EEDC) using Newton-Raphson load flow analysis to study the load flow in terms of active power, reactive power, and power factor of the Nigerian 11KV distribution system. All calculations have been performed in the per unit system with a three-phase complex power base SB = 100MVA and base voltage VB = 11KV. The feeder has a total installed power of 7.5MVA with an average power factor of (1.0 + 5% p.u), and the results of the process are presented in Table 1 for the 24-bus system.

Table 1: Result of characterization (Source EEDC)

Bus ID	Power factor	P load (kva)	Qload (kvar)
1	1.022	6.59	3.00
2	1.001	6.05	3.03
3	1.023	6.55	4.03
4	1.031	6.94	4.02
5	0.998	6.00	4.00
6	0.937	6.06	4.00
7	1.001	6.20	4.00
8	1.016	6.01	4.00
9	0.699	6.09	4.07
10	0.929	6.24	4.14
11	1.001	6.09	4.07
12	1.014	6.09	4.05
13	0.599	6.07	4.04
14	0.979	6.03	4.01
15	0.679	6.11	4.08
16	0.645	6.00	4.00
17	0.478	6.12	4.00
18	0.977	6.14	4.00
19	1.015	6.07	4.03
20	0.679	7.09	4.08
21	0.645	6.90	4.00
22	0.478	6.88	4.00
23	0.977	5.54	4.00
24	1.015	5.07	4.03
Average	0.86825	6.205	3.95

The data in the table1 was analyzed using excell software to determine the behavior of the feeder. From the result of the load flow data collected, it was observed that the average power factor is 0.868 which is below the tolerated power factor value of ±5% (1.00) and hence there is need for improevment and power system correction.The model of the load flow algorithm is used to study the feeder is presented in figure 1;

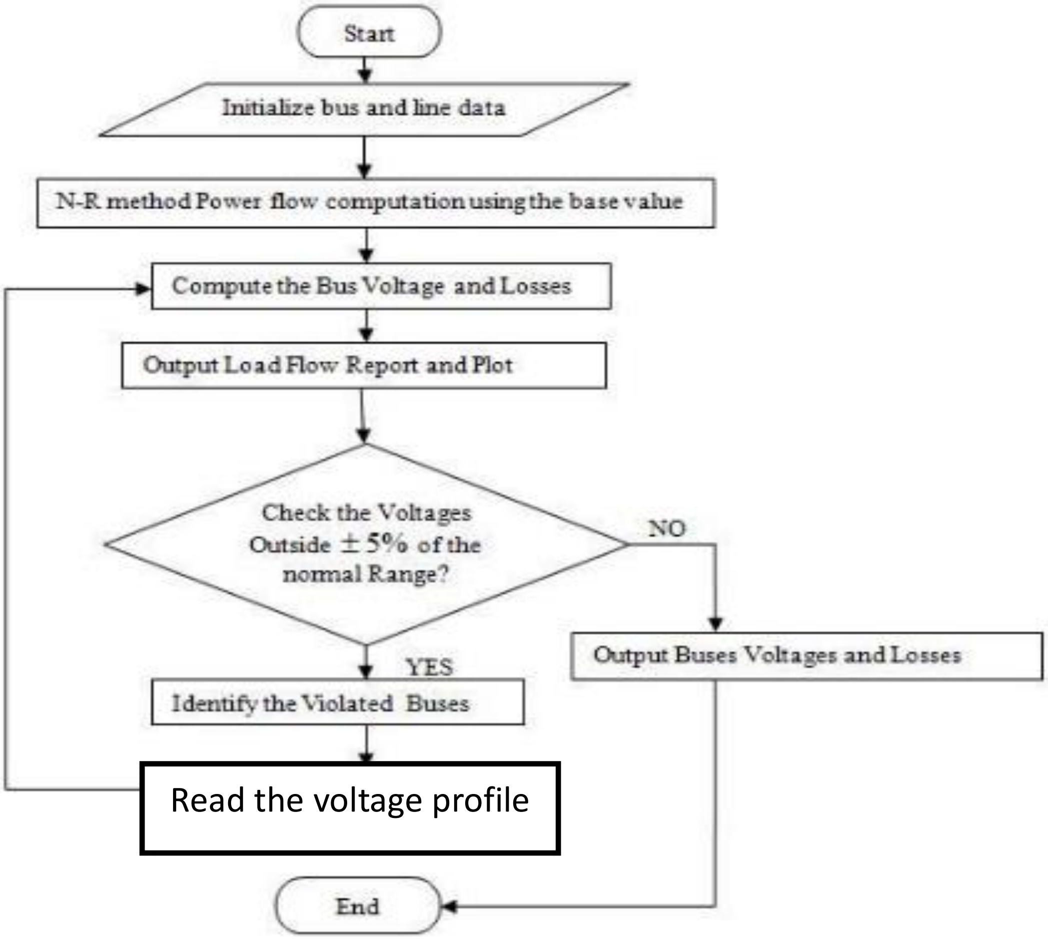

Figure 1: Flow chart of the load flow algorithm used for the data collection

3.1 Development of the shunt bank

Shunt banks are inductive and capacitive device installed to provide capacitive reactive and active compensation or power factor correction. When the voltage is low the shunt generates reactive power (capacitive bank) while when voltage is high, it absorbs reactive power (inductive bank). This variation of reactive power is performed by switching three phase capacitor and inductor banks connected on the secondary side of the coupling transformer. The capacitive bank is designed using external fuse to ensure the protection of the transformer against fault. Capacitors are designed to operative at or below the rated voltage and frequency as they are very sensitive to these values, the reactive power P(kVar) generated a capacitor is defined using the model below;

$$(P(kVar) = 2 * 3.142\, fV^2) \qquad 1$$

3.2 Bank Configuration with external fuse

The bank is configured using protection fuse element. The fuse is mounted between the capacitor unit and the bank fuse bus to protect the capacitor unit. Externally fused SCBs are configured using one or more series groups of parallel-connected capacitor units per phase (Fig. 2). The available unbalance signal level decreases as the number of series groups of capacitors is increased or as the number of capacitor units in parallel per series group is increased. However, the kiloVar rating of the individual capacitor unit may need to be smaller because a minimum number of parallel units are required to allow the bank to remain in service with one fuse or unit out.

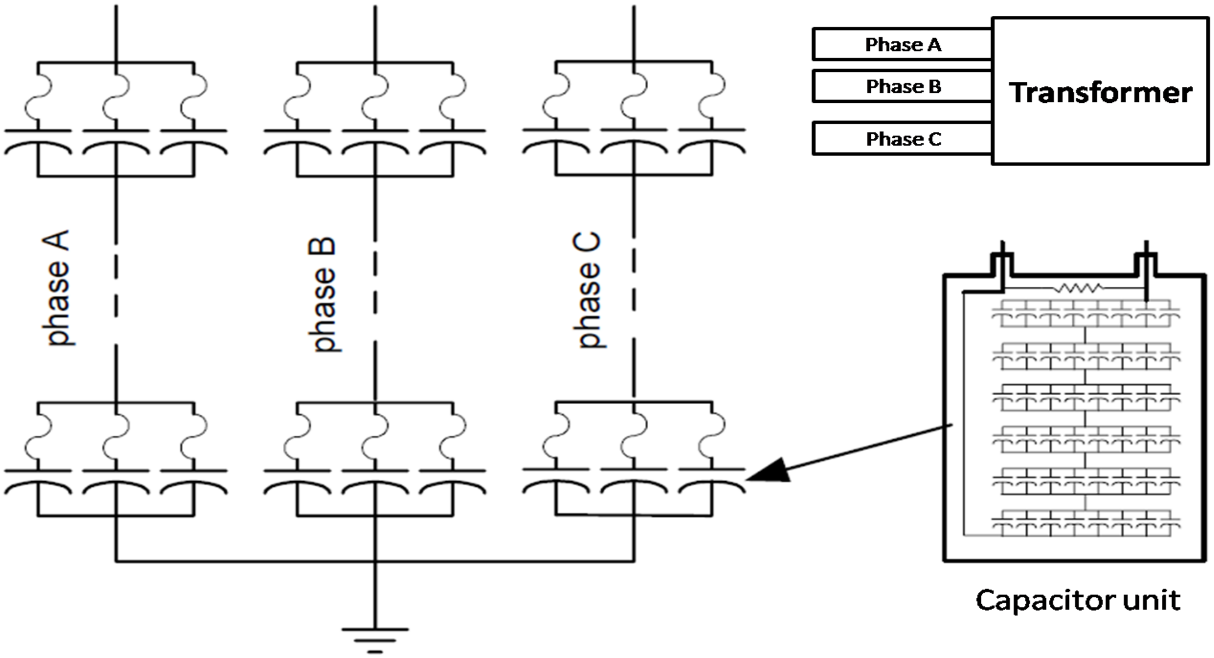

Figure 2: capacitive bank configuration

4. IMPLEMENTATION OF THE SYSTEM DEVELOPED

The Simulink implementation for this study was crucial in evaluating the effectiveness of integrating a shunt capacitor bank to optimize the power factor of the distribution transformer. The process involved several steps to ensure accurate simulation and analysis. To start with, a detailed Simulink model was developed to represent the distribution transformer and the shunt capacitor bank accurately. This model encompassed the electrical characteristics of the transformer, such as impedance, voltage rating, and power rating, along with the specifications of the capacitor bank. Next, the components of the shunt capacitor bank were integrated into the Simulink model at the secondary side of the transformer. This integration involved connecting the capacitors in parallel with the load to provide reactive power compensation and improve the power factor. The parameters of the shunt capacitor bank, including capacitance values and switching mechanisms, were parameterized within the Simulink model for easy adjustment and optimization. The sizing of the capacitor bank was based on calculations to ensure optimal performance. The Simulink simulation was then set up to replicate real-world operating conditions and load scenarios. This involved defining input voltage waveforms, load profiles, and other relevant parameters to accurately reflect the system's behavior. During the simulation, the performance of the distribution transformer with and without the shunt capacitor bank was evaluated. Key metrics such as power factor, voltage regulation, and efficiency were monitored and analyzed to assess the impact of the capacitor bank on transformer performance. The results obtained from the simulation were compared with those of the transformer without the shunt capacitor bank, allowing for a quantitative assessment of the improvement achieved. This comparative analysis provided insights into the effectiveness of the capacitor bank in enhancing power factor and overall performance efficiency.

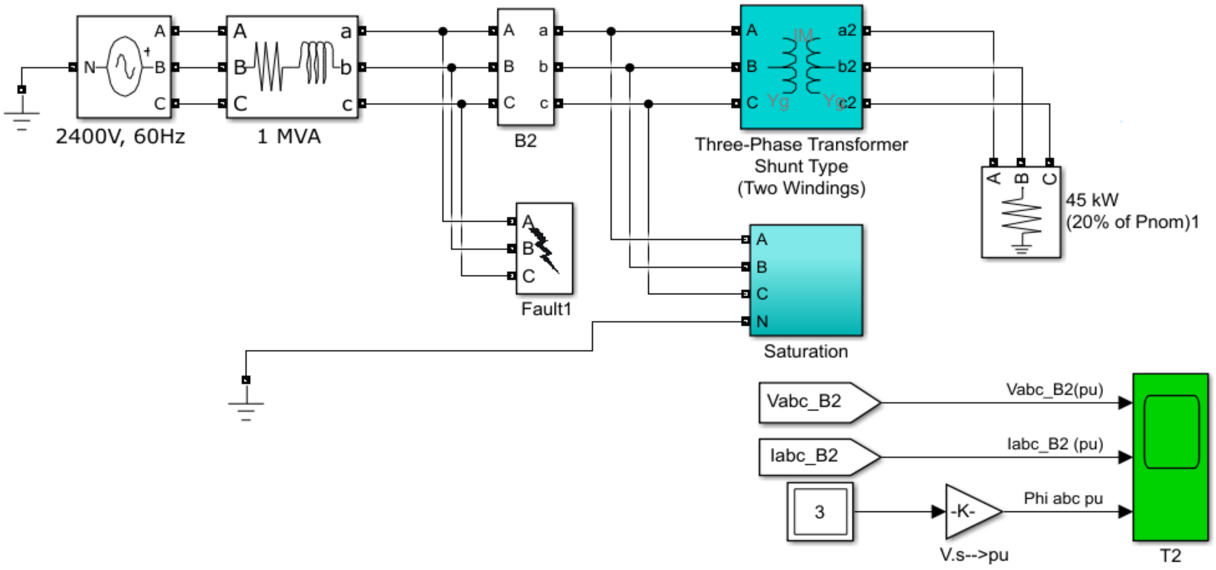

Figure 3: Simulink model of the 11KV transformer

The figure 3 presented the 11Kv transformer model implemented with Simulink. The model was developed using the voltage and flux current characteristics. The power factor of this transformer was then improved using the Simulink model of the shunt capacitor below.

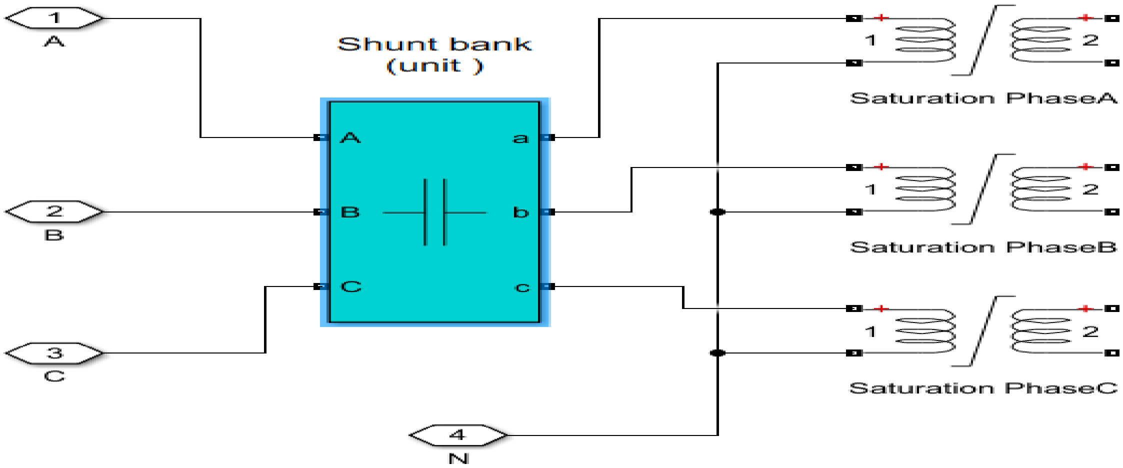

Figure 4: Simulink model of the shunt capacitor bank

5. RESULTS AND DISCUSSIONS

This section presented the results and discussion of the simulated model developed in the previous chapter. The result tested the power factor of the transformer and the effectiveness of the capacitor shunt system using simulated single phase fault condition. The simulation parameters are presented as shown in table 2;

Table 2: Simulation parameters

Parameters	**Values**
Power system capacity	7.5MVA
Transformer type	Three phase power transformer
Primary Inductance	0.5H
Total reactive power	600Mvar
Frequency	60Hz
Start time	0.06s
Base voltage	11KV
Number of Phases	Three phase and neutral
DC components	4.849e + 04
Samples per cycle	614
Primary Inductance	0.5H

The results below presented the performance of the transformer during on load and with the shunt capacitor system integrated. The result achieved using the testbed data to simulate the models developed with simulink and the result of the load flow was presented in figure 5;

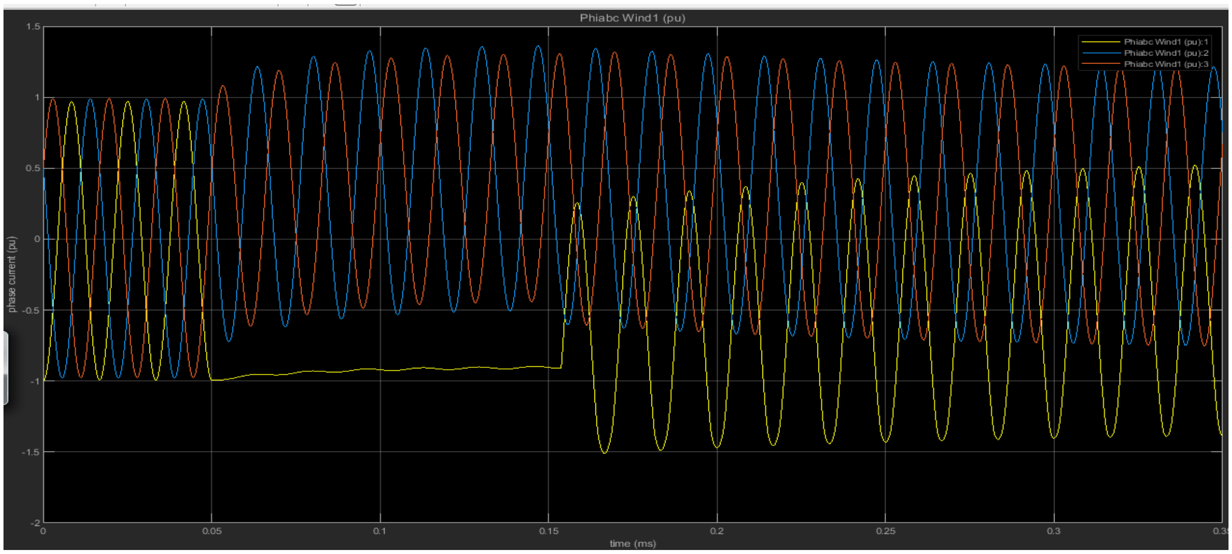

Figure 5: transformer performance

The result presented the performance of the transformer during line to ground fault. The figure 5 shows the three voltage magnitudes of the transformer oscillating. However after 0.05s, single line to ground fault occurred in the lines causing excess reactive current to flow. The excess reactive current is presented as shown in the figure 6;

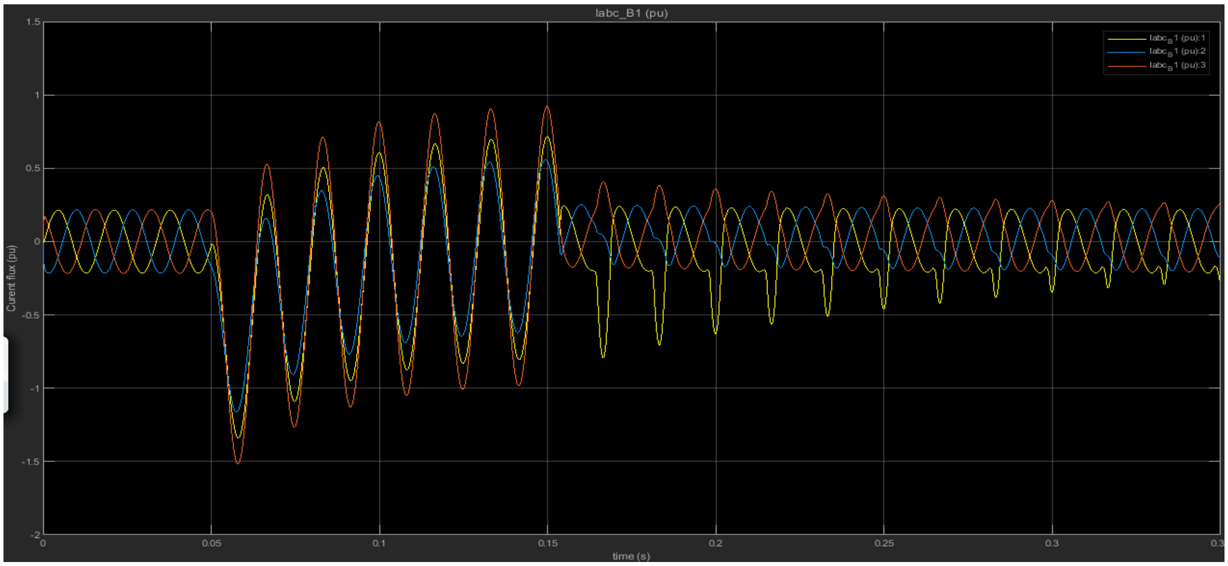

Figure 6: flux current from the transformer

The figure 6 presented the flux current which flows from the lines into the transformer thus generating reactive current. It was then observed that at 0.15s the shunt capacitor was able to absorb the reactive current using the injected shunt inductance and gradually neutralize the fault a shown in the voltage magnitude in figure 7.

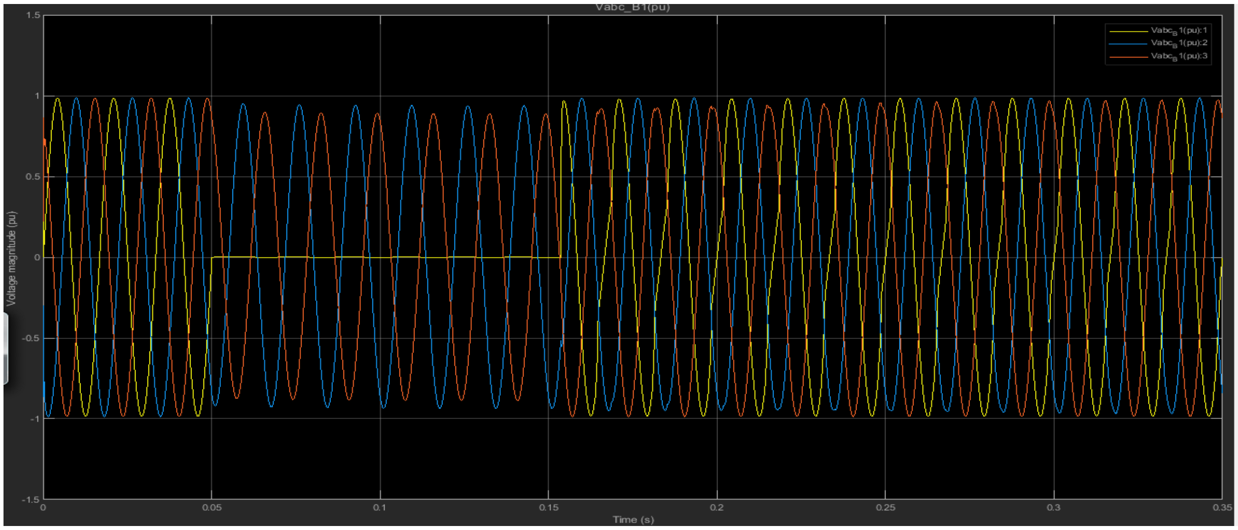

Figure 7: voltage magnitude

The figure 7 shows that at 0.05s, which fault occurred, the voltage magnitude which indicated the faulty line was dropped significantly, but when the shunt capacitor has absorbed that reactive current using the inductance and stabilize the system, the voltage magnitude after 0.15s becomes 0.987(pu). The shunt capacitor bank was deployed in the three transformers characterized with low power factor due to poor power factor and the result was presented based on the load flow as shown in table 3;

Table 3: transformer performance with shunt capacitor

Time (hr)	V (pu)
1	1.022
2	1.001
3	1.023
4	1.031
5	0.998
6	0.937
7	1.001
8	1.016
9	0.994
10	0.929
11	1.001

12	1.014
13	0.959
14	0.979
15	0.979
16	0.945
17	0.978
18	0.977
19	1.015
20	0.979
21	0.979
22	0.945
23	0.978
24	0.977
Average	0.985

The table 3 presented the performance of the shunt capacitor based transformer. From the result, it was observed that the average voltage factor after 24hr performance is 0.985p.u which is within the recommended standard for optimized transformer efficiency. The next result presented the system comparative analysis as in table 4;

Table 4: Comparative analysis

Time (hr)	V (pu) without capacitor	V (pu) with capacitor shunt
1	1.022	1.022
2	1.001	1.001
3	1.023	1.023
4	1.031	1.031
5	0.998	0.998
6	0.937	0.937
7	1.001	1.001
8	1.016	1.016
9	0.699	0.994
10	0.929	0.929
11	1.001	1.001
12	1.014	1.014
13	0.599	0.959
14	0.979	0.979
15	0.679	0.979
16	0.645	0.945
17	0.678	0.978
18	0.977	0.977
19	1.015	1.015
20	0.679	0.979
21	0.645	0.979

22	0.678	0.945
23	0.977	0.978
24	0.915	0.977

The table 4 presented the comparative performance of the transformer within 24hours of operation with the power factor analyzed. The result showed that the average power factor of the transformer with the shunt capacitor is 0.987p.u and without the capacitor is 0.881p.u. The percentage increase in performance of the new transformer power factor is 6.35% compared to the characterized.

6. SUMMARY

This study developed a shunt capacitor and intelligently deployed into the transformers as a backup protection against fault conditions. The result when tested showed that the shunt was able to inject active current with the inductance when power factor is low and absorb reactive current with the capacitance when power factor is very high. This process ensured power stability and quality of voltage supplied in the network. The system was implemented with Simulink and tested. The result showed that an improved power factor of 6.35% was achieved.

7. REFERENCES

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