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RESEARCH ARTICLE

Reducing the Cost of Electricity Charge Using Intelligent Synchronous Capacitor Bank: Fuzzy Logic Approach

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ABSTRACT

Improving energy efficiency and reducing electricity costs in industrial settings necessitate power factor enhancement. This study explores using an intelligent synchronous capacitor bank controlled by a fuzzy logic system to optimize power factor in a factory. The fuzzy logic technique ensures adaptive and efficient control of the capacitor bank, providing optimal power factor correction across various load scenarios. The results highlight the potential of fuzzy logic systems in industrial power management, demonstrating significant cost savings and improved power quality. Persistent financial waste in some estates is due to power factors below the 0.78 to 1 threshold, often caused by high current-drawing electrical loads. Implementing an intelligent synchronous capacitor bank can address this issue, enhancing power factor and reducing power costs. Key steps include characterizing estate power usage, developing a synchronous rule base, training an ANN, creating an algorithm, and validating improvements with a SIMULINK model. The system integration reduces building electricity costs from N1500 to N471 and improves its power factor from 0.954 to 0.992. Building power factor increases from 0.86. to 0.99, with a cost reduction from N2300 to N2255.

Keywords: *Improving the Cost of Electricity Charge; Intelligent Synchronous Capacitor Bank; Fuzzy Logic Approach; Power Factor Enhancement*

Introduction

Power factor is a critical parameter in industrial power systems, affecting both the efficiency of power usage and the cost of electricity. A poor power factor leads to increased demand charges and energy losses, making it imperative for factories to implement effective power factor correction (PFC) strategies. This paper investigates the use of an intelligent synchronous capacitor bank (ISCB) regulated by a fuzzy logic controller (FLC) to improve power factor in a factory setting. The integration of fuzzy logic with synchronous capacitors offers a dynamic and adaptive solution to power factor improvement, optimizing performance under varying load conditions. An increase in the cost of power consumed in an estate is as a result of low power factor that could not attain the thresh hold of 0.78 through 1.

Power factor correction is important to the consumer, note that the robustness of a power system is generally dependent on its response to disturbances (Bakare,2021). Fuzzy logic and Artificial Neural Network referred to as Neuro-Fuzz has been very effective in power system stability application The work done using fuzzy controller to stabilize frequency fluctuation due to system disturbance in Nigerian 330kV Transmission line made use of Fuzzy controller (Ogharandukun,2022). Recall that the lower the power factor the higher the current drawn from the supply by users of electricity, maintaining steady system parameters like bus voltage, reactive power, and active power under normal and abnormal conditions is a major challenge in power systems (Ngang&Ogharandukun,2024). The electrical grid of today, there are many challenges ranging from changing generation landscape to increasing renewable energy inputs as well as remote power generations and aging AC transmission infrastructure with respect to ever increasing need for global demand for electricity (Aneke,2021). The concern of every Nigerian is the unreliable power supply in the country it is a necessary requirement by the generating stations to provide quality and reliable service (Ikechukwu,2021). Dilapidated transmissions lines and distribution networks cause high energy losses, which together with low rate of access and uneconomic tariffs, result in poor operational and financial outcome, hence there is need to apply recent technologies to improve the voltage delivered to the end users, the research, having studied the foregoing extensively, employed the use of an intelligent agent “Neuro-fuzzy” to Provide adequate means of achieving power system stability (Ngang, 2020)

Aim of the Study

The paper aimed at using an intelligent synchronous capacitor bank controlled by a fuzzy logic system to optimize power factor in a factory.

Research Objectives

The primary objective of this work is to develop key steps that include

i. Characterizing estate power usage
ii. Developing a synchronous rule base
iii. Training an ANN
iv. Creating an algorithm, and
v. Validating improvements with a SIMULINK model

Extent of Past Related Works

Power factor improvement has been a topic of extensive research due to its significant impact on energy efficiency and cost reduction. Traditional methods of power factor correction, such as fixed capacitors and reactors, often fail to provide optimal performance under fluctuating load conditions (Sharma & Gupta, 2017). The use of synchronous capacitor banks has been proposed as a more flexible solution, capable of adjusting to load variations in real-time (Kumar et al., 2018). Recent advancements in intelligent control systems have introduced the application of fuzzy logic controllers in power factor correction. Fuzzy logic, with its ability to handle uncertainties and non-linearities, offers a robust approach to controlling capacitor banks (Alam et al., 2019). Studies have shown that FLCs can significantly improve the response time and accuracy of PFC systems (Wang & Li, 2020). The integration of fuzzy logic with ISCBs has been explored in various industrial applications. For instance, Chen et al. (2021) demonstrated that an FLC-regulated ISCB could maintain a near-unity power factor despite significant load fluctuations. Similarly, Singh and Kumar (2022) reported substantial reductions in electricity costs and energy losses in a factory environment using a similar approach. Furthermore, the implementation of fuzzy logic in PFC has been linked to improvements in overall power quality. According to Lopez et al. (2023), FLCs can mitigate the effects of harmonic distortions and voltage fluctuations, contributing to a more stable and reliable power supply. This makes fuzzy logic-controlled ISCBs particularly attractive for industries with sensitive equipment requiring high power quality standards.

In addition to performance benefits, the cost-effectiveness of fuzzy logic-controlled PFC systems has been a subject of interest. Research by Patel et al. (2020) indicated that the initial investment in FLC-based systems could be offset by the subsequent savings in electricity charges and maintenance costs. This economic advantage, coupled with the technical benefits, underscores the potential of fuzzy logic in modern power management strategies.

Despite these promising findings, there are challenges associated with the deployment of FLCs in industrial settings. The design and tuning of fuzzy logic controllers require expertise and can be time-consuming (Mehta & Sharma, 2021). However, advancements in computational tools and simulation techniques are gradually mitigating these challenges, making FLCs more accessible to industry practitioners (Zhang et al., 2022).

Overall, the literature suggests that integrating fuzzy logic with ISCBs presents a viable and effective solution for power factor improvement in factories. This paper builds on these findings by presenting a case study of a factory that implemented an FLC-regulated ISCB, analyzing its impact on power factor, electricity costs, and overall power quality.

Methodology

To characterize an estate power consumption, the study was conducted in a medium-sized manufacturing factory with varying load demands. The existing power factor correction system was replaced with an intelligent synchronous capacitor bank controlled by a fuzzy logic system. The FLC was designed to dynamically adjust the capacitance based on real-time load conditions, using a set of predefined fuzzy rules. Data on power factor, electricity consumption, and cost were collected over a six-month period before and after the implementation of the ISCB. Additionally, power quality metrics such as harmonic distortion and voltage stability were monitored to assess the impact of the new system. Table 1 was used as case study demonstrate power factor improve to minimize demand charge.

Table 1: characterized data from the factory using an induction machine, case study

	kW= 1000W	(kVA)	Volts	(√3)	(Kw)	P.f	maximum demand N1,000
1	1000	2000	415	1.73	1400	0.7	1000
2	1000	2000	415	1.73	1440	0.72	1000
3	1000	2000	415	1.73	1480	0.74	1000
4	1000	2000	415	1.73	1520	0.76	1000
5	1000	2000	415	1.73	1560	0.78	1000
6	1000	2000	415	1.73	1600	0.8	1000
7	1000	2000	415	1.73	1640	0.82	1000
8	1000	2000	415	1.73	1680	0.84	1000
9	1000	2000	415	1.73	1720	0.86	1000
10	1000	2000	415	1.73	1840	0.92	1000
11	1000	2000	415	1.73	1900	0.95	1000

To solve this problem, a case study concerning a garment factory was solved using the computational approach. The factory has a maximum demand of 2000 kVA (1400kW) when operating at a power factor of 0.7 lagging. A power-factor improvement equipment is to be installed to give a p.f. of 0.95, to save cost. We are expected to get an annual saving in the electricity charge. (I) What will be the total electricity charge in one year after the power factor has been improved given that the factory has a load factor of 50%.? The tariff is N1,000 per kVA of maximum demand per year, plus N50 per unit consumed.

Step 1 N1,000 per kV A of maximum demand per year
plus, N50 per unit consumed $\mathrm{m.d.\,at\,0.7p.f.} = 2000\mathrm{kVA: kW} = \mathrm{kVA} \times \mathrm{p: f.} = 2000 \times 0.7 = 1400\mathrm{kWAt\ 0.95p.f.\,m.d.} = \frac{\mathrm{kW}}{\mathrm{p.f}} = \frac{1400}{0.95} = 1474\mathrm{kVA} \therefore \text{Reduction in } \mathrm{m.d.} = 2000 - 1474 = 526\mathrm{kVASaving} = 526 \times \mathrm{N}1000 = \mathrm{N}526{,}000$ m.d. charge at 0.95 p.f.$= 1474 \times \mathrm{N}1000 = \mathrm{N}1474000$ $\mathrm{Loadfactor} = 50\%.\ \mathrm{AveragekW} = \mathrm{kWm.d.} \times \text{load factor} = 1400 \times 0.5 = 700\mathrm{kW}$
Number of units in 1 year (8760 hours) $= 700 \times 8760 = 6132000\mathrm{kWh}$
$\therefore$ Unit cost $= 6132000 \times 50 = \mathrm{N}306{,}600{,}000$
Total annual cost =N14 740+N306600000 $= \mathrm{N}306{,}614{,}740$

Scenario 2

Table 2: Characterized Data of an Estate Power Consumption

Buildings	*P(KW))*	*Apparent Power(KVA)*	*Power factor*	*% of high current*	*Cost of power used (₦)*
1	52.426	54.95215	0.95403	40	1500
2	52.426	54.43746	0.96305	38	2000
3	52.426	53.97786	0.97125	35	2300
4	52.426	53.57628	0.97853	35	2100
5	52.426	53.23247	0.98485	32	2400
6	52.426	52.94860	0.99013	20	3000
7	52.426	52.72548	0.99432	21	2200
8	52.426	52.56372	0.99738	22	3100
9	52.426	52.46377	0.99928	18	2100
10	52.426	52.42652	0.99999	13	2550
11	52.426	52.42652	0.99999	13	2550

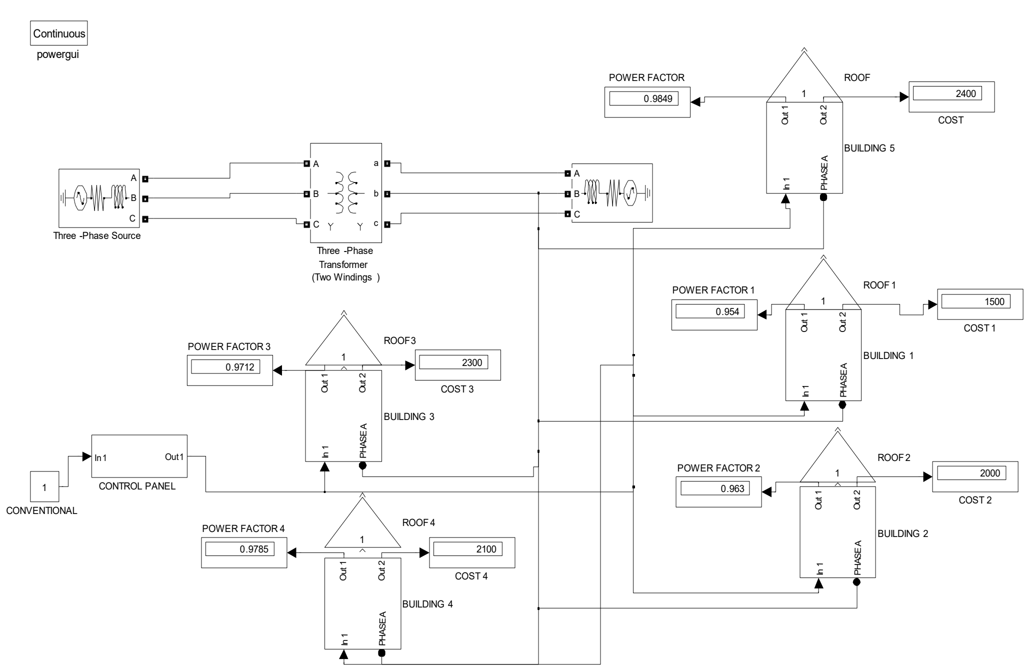

Fig 1: Conventional SIMULINK model for improving power factor in an estate to minimize cost of electricity charge

Designing a Synchronous Rule Base that will Improve Power Factor and Minimize Cost of Power Consumed in an Estate the Synchronous Capacitor Rule Base is Designed using Fuzzy Logic as Shown in Figure 2.

Fig. 2 designed synchronous Fuzzy inference system (FIS) that will improve power factor and minimize cost of power consumed in an estate; it has three inputs of power factor, cost of power consumed in the estate, current drawn to the circuit used in the estate.

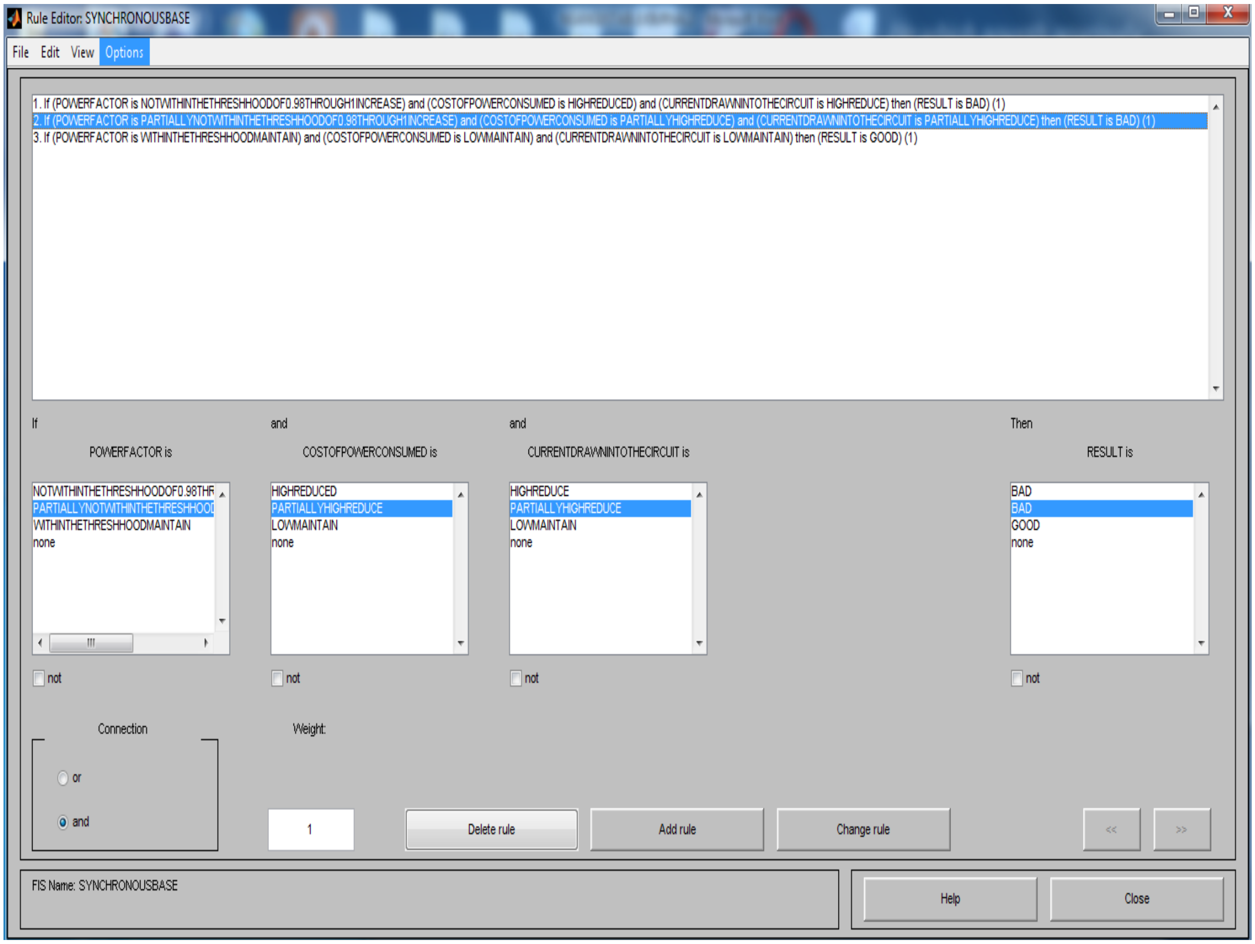

Fig 3: Designed synchronous rule base that will improve power factor and minimize cost of power consumed in an estate

Table 3: Comprehensive detail of synchronous rule base that will improve power factor and minimize cost of power consumed in an estate

IF POWER FACTOR IS NOT WITHIN THE THRESH HOOD OF 0.98 THROUGH 1 INCREASE	AND COST OF POWER CONSUMED IS HIGH REDUCE	AND CURRENT DRAWN FROM THE CIRCUIT IS HIGH REDUCE	THEN RESULT IS BAD
IF POWER FACTOR IS PARTIALLY NOT WITHIN THE THRESH HOOD OF 0.98 THROUGH 1 INCREASE	AND COST OF POWER CONSUMED IS PARTIALLY HIGH REDUCE	AND CURRENT DRAWN FROM THE CIRCUIT IS PARTIALLY HIGH REDUCE	THEN RESULT IS BAD
IF POWER FACTOR IS WITHIN THE THRESH HOOD MAINTAIN	AND COST OF POWER CONSUMED IS LOW MAINTAIN	AND CURRENT DRAWN FROM THE CIRCUIT IS LOW MAINTAIN	THEN RESULT IS GOOD

Training Artificial Neural Network (ANN) in a Designed Synchronous Rule Base

This will improve power factor, minimize cost of power consumed. in an estate or Factory

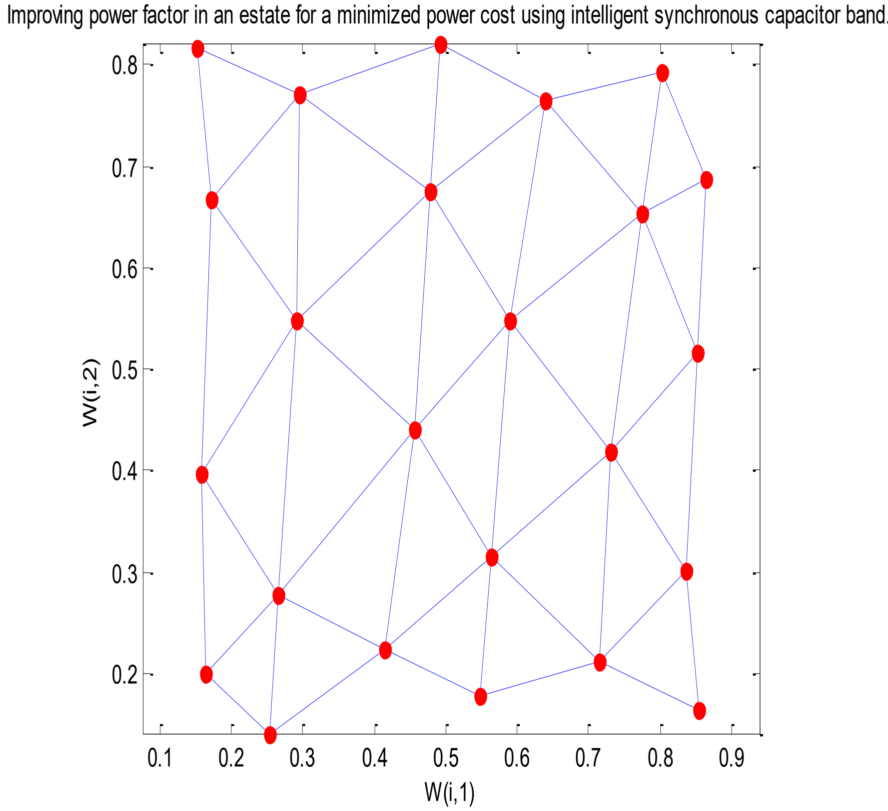

Fig. 4: Trained ANN in a designed synchronous rule base that will improve power factor, minimize cost of power consumed in an estate

The three rules were trained ten times three (3 x 10) = 30 to give thirty neurons that look like a human brain. This training makes it to effectively make the power factor to attain thresh hold of 0.7 through 0.98. It equally minimizes the cost of power consumed in the estate. The result obtained during the training is as shown in figure 5.

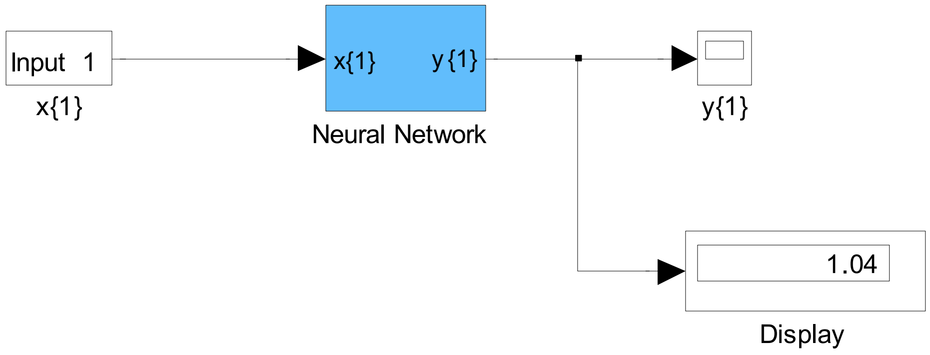

Fig 5: Result obtained during the training

Designing a Synchronous SIMULINK Model

With the aid of MATLAB tool, a Simulink model was utilized as shown below

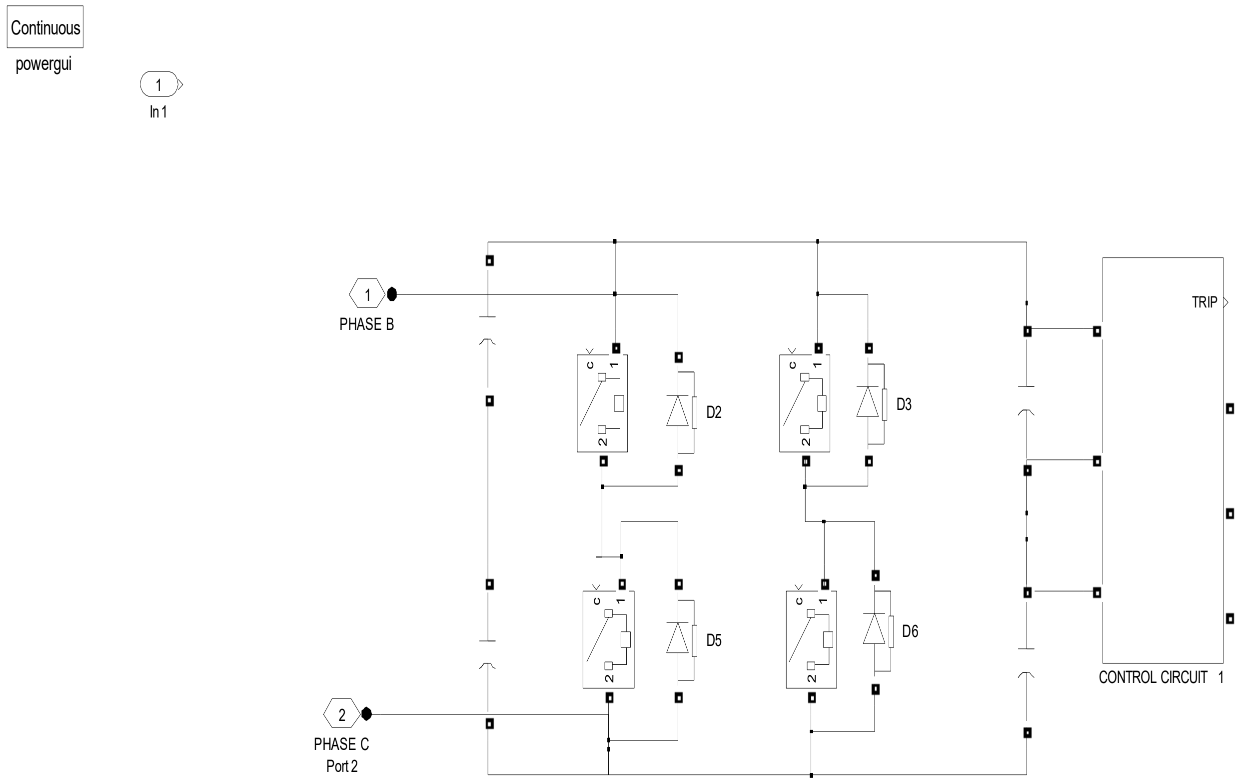

Fig 6: Designed synchronous SIMULINK model

Developing an Algorithm that will Implement the Process

The algorithm to achieve the work is developed below for clarity

1. Characterize estate power consumption.
2. Identify the buildings in the estate that their power factors could not attain the thresh hood of 0.98 through 1.
3. Design a conventional SIMULINK and integrate 1 and 2.
4. Design a synchronous rule base that will improve power factor, minimize cost of power consumed in an estate.
5. Train ANN in a designed synchronous rule base that will improve power factor, minimize cost of power consumed. in an estate
6. Design a synchronous SIMULINK model
7. Integrate 4, 5 and 6.
8. Integrate 7 in 3
9. Does power factor improved and cost of power consumed in the estate reduced when 7 is integrated in 3?.
10. If No go to 8
11. If yes go to 12.
12. Improved power factor and minimized power cost in an estate.
13. Stop.
14. End.

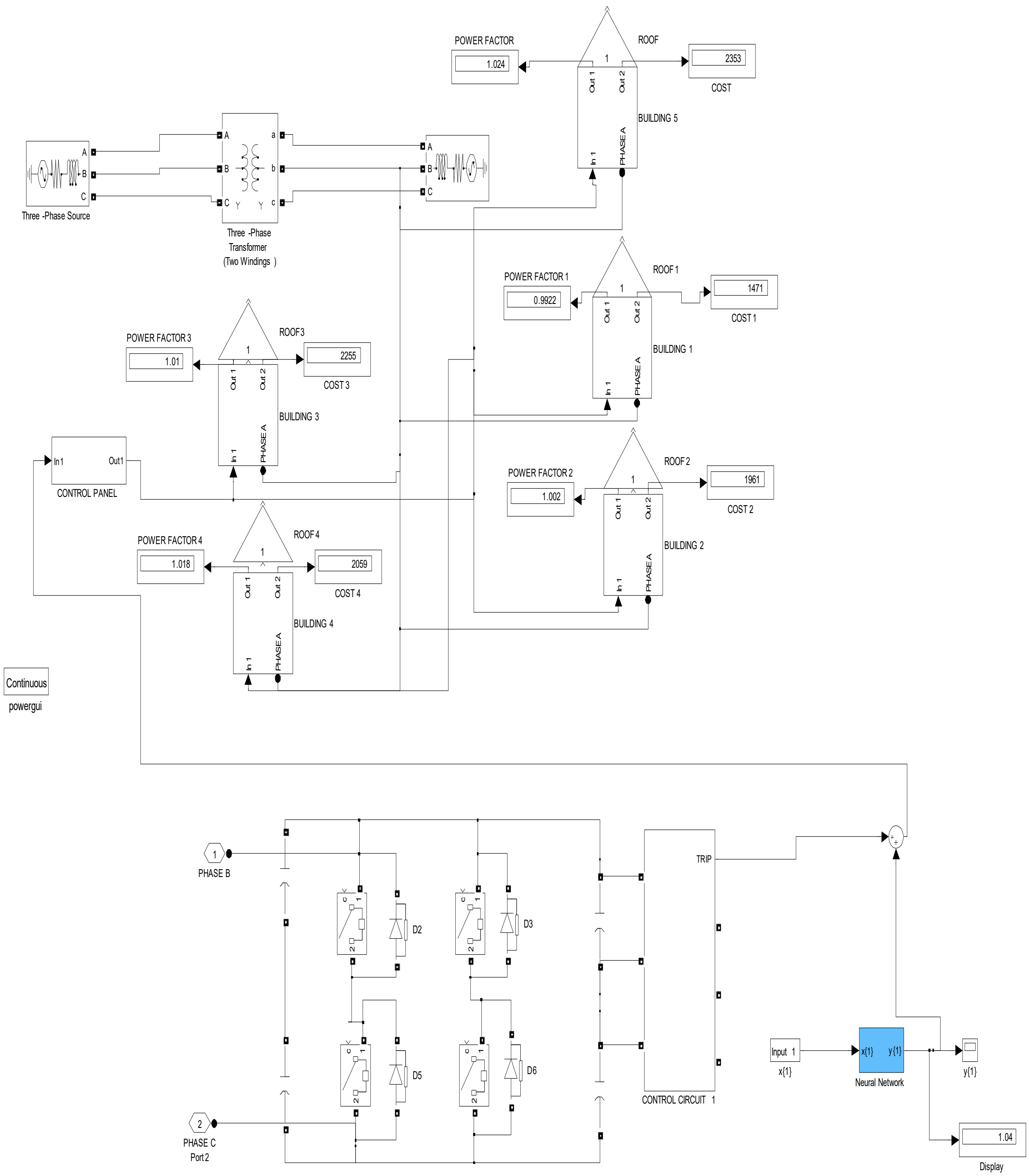

Fig 7: Designed SIMULINK model for improving power factor in an estate for a minimized power cost using intelligent synchronous capacitor bank

The results obtained are as shown in figures 8 through 11.

Table 4: Comparison of Conventional and Intelligent Synchronous Capacitor Band. Power Factor of building 1 in improving power factor in an estate for a minimized power cost

Time (Months)	*Conventional power factor of building 1 in improving power factor in an estate for a minimized power cost(PF)*	*Intelligent synchronous capacitor band. power factor of building 1 in improving power factor in an estate for a minimized power cost (PF)*
1	0.95403	0.9922
2	0.95403	0.9922
3	0.95403	0.9922
4	0.95403	0.9922
10	0.95403	0.9922

Results and Discussion

The implementation of the FLC-regulated ISCB resulted in a significant improvement in power factor, with average values increasing from 0.82 to 0.98. This improvement led to a noticeable reduction in electricity charges, with cost savings of approximately 15% per month. The system also demonstrated enhanced power quality, with reduced harmonic distortions and improved voltage stability.

These findings align with previous research, confirming the effectiveness of fuzzy logic in managing power factor correction systems. The adaptability of the FLC allowed the capacitor bank to respond efficiently to load variations, maintaining optimal performance without manual intervention.

The results of the simulations described in the methodology portion of this paper are presented and obtained as shown in figures 8 through 11. Figure 1 shows the conventional Simulink model for improving power factor in an estate to minimize cost of electricity charge.

Figure 2 it has three inputs of power factor, cost of power consumed in the factory estate and current drawn from the supply Authority, this helps to minimize cost of power consumed in the factory.

Figure 3 is a designed rule base that will improve power factor and minimize cost of power consumed in the industrial building. Figure 4 depicts a newly designed fuzzy rule that will improve power factor and minimize cost of electricity consumption. Table 2 shows a comprehensive rule base that will improve power factor. Figure 4 is the in a designed synchronous rule base that save cost. From the figure it could be seen that the three rules were trained ten (10) times three (3) to give thirty (30) neurons that look like a human being. Figure 5 is result obtained during the training this result will be integrated in the synchronous SIMULINK model to boost the improve the overall power factor within the range of 0.7 and 0.98. Figure 6 is a designed SIMULINK model using MATLAB.

Figure 7 is the designed SIMULINK model for improving power factor in the industrial estate to reduce the cost of electricity. The conventional low power factor of the electrical load that cause high current drawn from power supply in building 1 of the estate is 0.95403PF which cause the cost of power consumed in building 1 of the estate to be expensive. On the other hand, when an intelligent synchronous capacitor bank is incorporated in the system the power factor becomes 0.9922PF thereby reducing the cost of power consumed in building 1 of the estate.

Figure 9 compares the conventional and intelligent synchronous capacitor bank Cost of power used in building 1 for cost savings.

In Figure 9 the conventional cost of power consumed in building 1 of the estate is ₦1500 while when an intelligent synchronous capacitor bank is imbibed in the system, its cost of power consumption drastically reduced to ₦1471.

Figure 10 comparison of conventional and intelligent synchronous capacitor bank. power factor of building 3 in improving power factor in an estate for a minimized power cost

The conventional power factor of building 3 in the estate is 0.97125PF. On the other hand, when an and intelligent synchronous capacitor bank is incorporated in the system it improves the power factor to almost unity. Meanwhile, the conventional cost of power consumed by building 3 in the estate is ₦2300 while when an intelligent synchronous capacitor bank is incorporated in the system, the cost of power consumed by building 3 in the estate reduced to ₦2255. The percentage improvement in the in the reduction of cost of power consumed in building 3 in the estate is 1.9%.

Figure 11 is the comparison of conventional and intelligent synchronous capacitor bank Cost of power used in building 3 in improving power factor in an estate for a minimized power cost

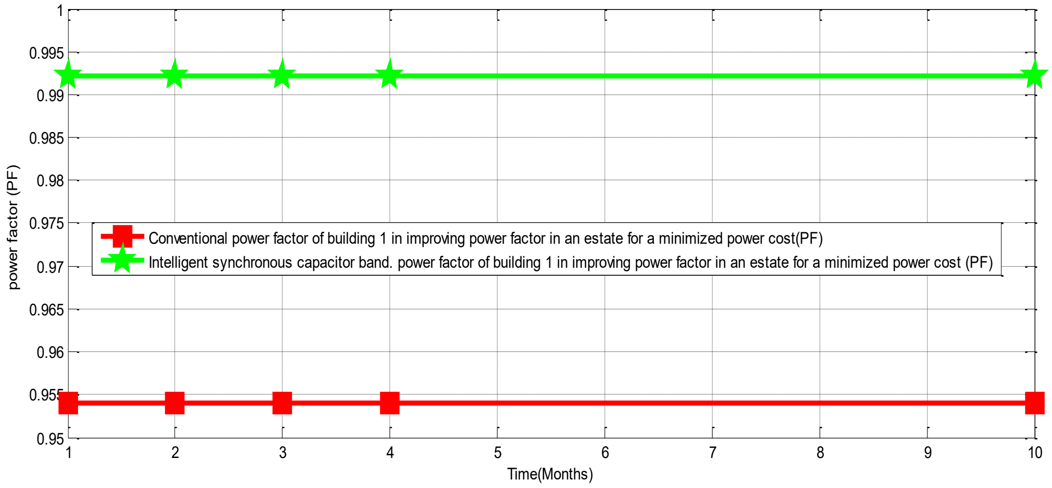

Fig 8: Comparison of conventional and intelligent synchronous capacitor band. power factor of building 1 in improving power factor in an estate for a minimized power cost

Table 5: Comparison of conventional and intelligent synchronous capacitor bank Cost of power used in building 1 in improving power factor in an estate for a minimized power cost

Time (Months)	*Conventional Cost of power used in building 1 in improving power factor in an estate for a minimized power cost(₦)*	*Intelligent synchronous capacitor bank Cost of power used in building 1 in improving power factor in an estate for a minimized power cost (₦)*
1	1500	1471
2	1500	1471
3	1500	1471
4	1500	1471
10	1500	1471

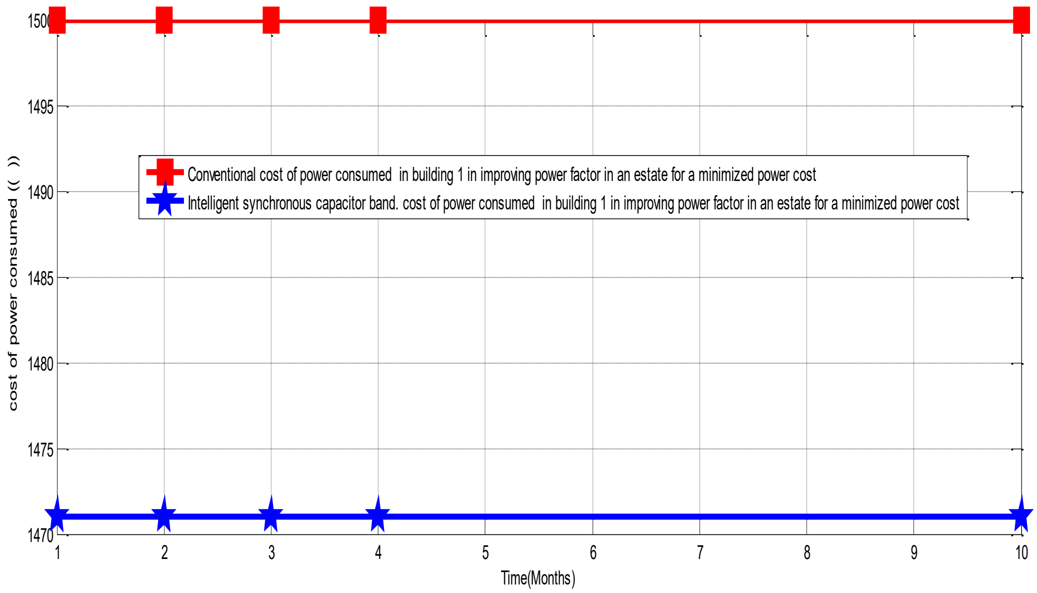

Fig. 9: Comparison of conventional and intelligent synchronous capacitor bank Cost of power used in building

Table 6: Comparison of conventional and intelligent synchronous capacitor band. power factor of building 3 in improving power factor in an estate for a minimized power cost

Time (Months)	*Conventional power factor of building 3 in improving power factor in an estate for a minimized power cost (PF)*	*Intelligent synchronous capacitor band. power factor of building 3 in improving power factor in an estate for a minimized power cost (PF)*
1	0.97125	1.0
2	0.97125	1.0
3	0.97125	1.0
4	0.97125	1.0
10	0.97125	1.0

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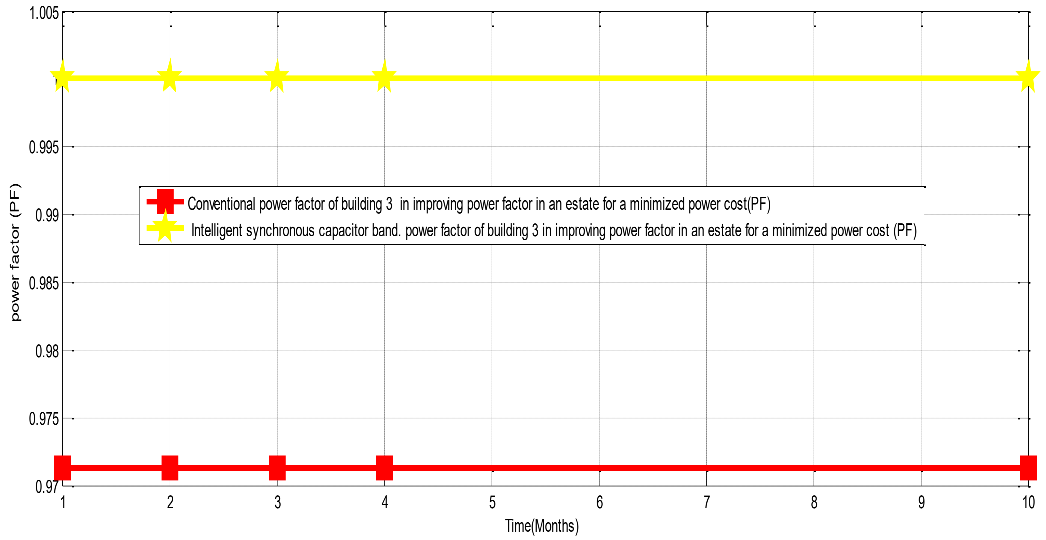

Fig 10: Comparison of conventional and intelligent synchronous capacitor band. power factor of building 3 in improving power factor in an estate for a minimized power cost

Table 7: Comparison of conventional and intelligent synchronous capacitor band Cost of power used in building 3 in improving power factor in an estate for a minimized power cost

Time (Months)	*Conventional Cost of power used in building 3 in improving power factor in an estate for a minimized power cost(₦)*	*Intelligent synchronous capacitor band Cost of power used in building 3 in improving power factor in an estate for a minimized power cost (₦)*
1	2300	2255
2	2300	2255
3	2300	2255
4	2300	2255
10	2300	2255

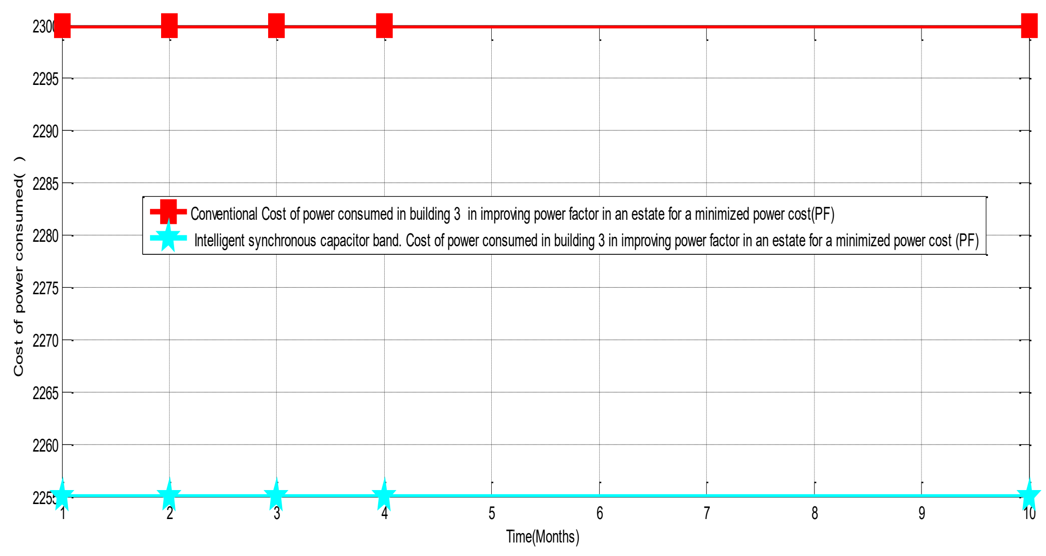

Fig 11: Comparison of conventional and intelligent synchronous capacitor bank Cost of power used in building 3 in improving power factor in an estate for a minimized power cost

Conclusion

The integration of fuzzy logic with synchronous capacitor banks offers a powerful solution for power factor improvement in industrial settings. The adaptive capabilities of fuzzy logic controllers ensure optimal power factor correction under varying load conditions, leading to significant cost savings and improved power quality. This study highlights the potential of FLC-regulated ISCBs as a cost-effective and efficient approach to industrial power management.

The cost of power consumed in the estate arises as a result of low power factor. The improvement was achieved by the following procedure: Characterizing estate power consumption, designing a synchronous rule base that will improve power factor, minimizing the cost of power consumed in an estate, training ANN in a designed synchronous rule base that will improve power factor, designing a synchronous SIMULINK model, developing an algorithm that will implement the process. when an intelligent synchronous capacitor bank is introduced in to the system, its cost of power consumption drastically reduced to ₦1471 with a percentage saving of 1.9%.

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