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Optimizing Energy-Efficient Home Electrical Systems through Capacitor Integration to Improve Future Energy Efficiency

Adi Nugraha[1,*], Felycia[1]

[1] *Electrical Engineering, Sultan Ageng Tirtayasa University, Cilegon, Indonesia*
**Correspondence author email: adi.n@untira.ac.id*

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ABSTRACT

This research discusses the optimization of energy-efficient home electrical systems through the integration of capacitors to improve future energy efficiency. The main objective is to analyze the impact of installing power capacitors in parallel with electrical loads such as fans, refrigerators, and computers to improve power factor and reduce energy consumption. An experimental approach is used, installing capacitors with different values (2μF, 6μF, 8μF) on the test loads and measuring parameters such as voltage, current, power factor, and active power. The results show that the installation of optimal capacitors (e.g., 2μF for fans, 8μF for refrigerators) significantly improves the power factor, from around 0.55-0.61 without capacitors to near unity with capacitors. This power factor improvement reduces the current flowing through the system, leading to lower active power losses and increased energy efficiency. For example, the fan current is reduced from 0.197A to 0.109A with a 2μF capacitor. The active power consumption also decreased for some loads, such as fans experiencing a 4.8% reduction, indicating energy savings. The capacitor integration provides economic benefits through reduced electricity costs and environmental benefits by lowering carbon emissions from reduced electricity generation. The key is to carefully select the right capacitor size to avoid over-compensation, requiring an analysis of the reactive power requirements for each load.

1. Introduction

Energy-efficient home electrical system is the concept of efficient management of electrical energy to reduce power consumption without reducing the comfort and functionality of electrical appliances in the home [1]. With the increasing need for energy and awareness of environmental impacts, this system is an important solution in creating environmentally friendly homes while saving operational costs [2]. The use of electrical devices labeled as energy-efficient is also an integral part of this system. Equipment such as LED lights, Energy Star standard electronic devices, and the use of inverters in air conditioners or water pumps help optimize electricity consumption [3].

In practice, an important parameter in determining the efficiency of electricity use is the power factor, which indicates the extent to which electrical energy is effectively utilized by a load [4]. A low power factor indicates the presence of a large reactive power component, thus increasing the current flow in the system [5]–[7]. This not only causes energy waste, but also results in active power losses in various elements of the electric power system, from the generating center to the end consumer [8]. To solve this problem, one effective solution is to install power capacitors in parallel in electrical installations [9].

The power capacitor serves as a reactive load balancer, thereby reducing the need for reactive power flow from the main source [10]. Thus, the capacitor helps to increase the cos phi value (power factor), which directly impacts the increase in the efficiency of electricity use [11]. Installing power capacitors in home electrical installations is one of the strategic steps [12]. This capacitor functions to reduce reactive power components, thereby reducing the current flowing and reducing active power losses in the home power grid [13]–[15].

This efficiency not only provides economic benefits in the form of reduced electricity costs, but also has a positive impact on reducing the heat generated due to excess current in the system. In addition, the increase in the power factor also helps to reduce the workload on transformers and other equipment, extending the technical life of such equipment. However, the application of capacitors must be done carefully with proper calculations. If the installed capacitor has too much capacity, this can lead to over-compensation, which is also undesirable. Therefore, an analysis of reactive power requirements is an important first step before installing capacitors.

This research presents innovations in household electrical system technology by utilizing the integration of power capacitors. This approach is designed to improve energy efficiency while providing economic and environmental benefits. One of the main focuses of the research is on the use of power capacitors to improve the power factor, which has an impact on reducing electrical energy consumption. This technology is still relatively new and has not been widely applied in households, so this research offers interesting practical application potential. The benefits resulting from this research include energy efficiency and electricity cost savings, where the integration of power capacitors is able to significantly reduce energy consumption. In addition, there are environmental benefits in the form of reduced carbon emissions due to a decrease in electricity consumption. Thus, this approach is not only economically beneficial, but also contributes to environmental sustainability.

2. Methods

The research method used in this study is a quantitative experimental approach, which aims to test the effect of the use of power capacitors on the efficiency of the household electrical system. In this method, direct testing is carried out by installing power capacitors on various types of electrical loads, such as fans, refrigerators, and computers. Measurements of electrical parameters, such as voltage, current, power factor, and energy consumption, are made before and after the installation of the capacitor to see the changes that occur. The data collection method in this study uses an observation approach. Observation is made by installing power capacitors on each load in parallel. This process involves hands-on experiments in the field to obtain accurate and relevant data. In each stage of the experiment, power capacitors are installed at different loads to observe their effect on the performance of the electrical system. Data collection is carried out by reading the measurement results obtained from the measuring tools used. The measuring device records important parameters such as current, voltage, and power consumed by the load. The data produced is in the form of quantitative numbers that reflect changes in system performance before and after the installation of power capacitors.

After the measurement is completed, the data obtained is carefully recorded and arranged in the form of a table. This table serves to facilitate data analysis and provide a clearer picture of the relationship between the observed variables. In the table, each column represents the parameter being measured, while each row represents the result of the experiment performed. The results of the data presented in the form of a table are then analyzed to determine the effectiveness of the installation of power capacitors. This analysis includes the calculation of power factors, system efficiency, and potential reduction in energy consumption.

2.1. *Research Materials*

In this study, there are several research materials, including the following:

1. **Power Capacitors**: Electronic components with capacitance values of 2 μF, 6 μF, and 8 μF, which are used to increase the power factor in electrical systems.
2. **Measuring Instrument**: *Digital Power Meter*, used to measure electrical parameters such as active power, reactive power, voltage, and current at the load being studied.

3. **Load Devices**: Computers, fans, and refrigerators are used as electrical loads for simulation in testing

2.2. *Network Schematics*

The series scheme in this study is as follows.

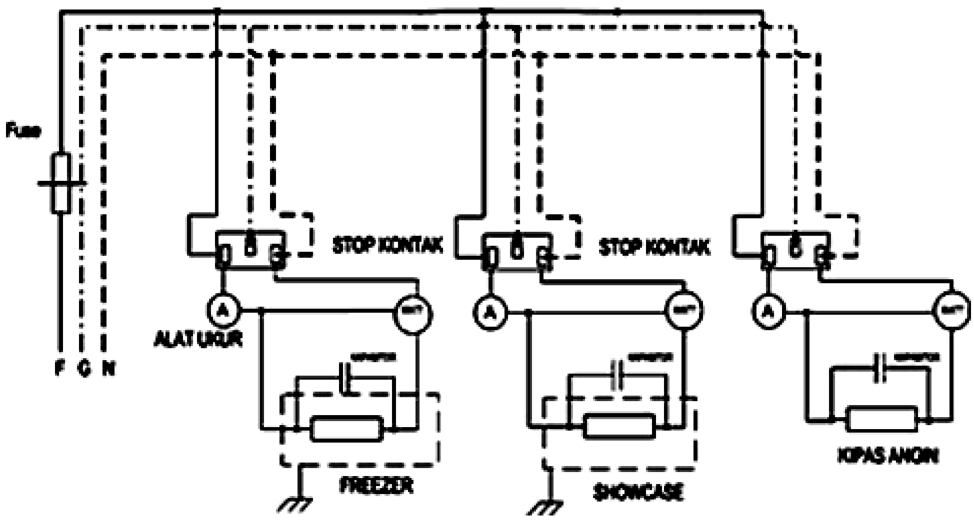

Figure 1. Capacitor Mounting Network Schematic

3. Results and Discussion

3.1. *Result*

This study discusses the quality of electrical load through the addition of power capacitors by producing quantitative data arranged in the form of tables. The data obtained includes measurements of various important parameters, namely voltage, current, active power, and power factor. This research is also a development of the previous journal, with modifications to the type of load and size of the capacitors used to observe their effect on electrical performance.

The object of the study consists of three electrical loads in the household environment, such as fans, refrigerators, and computers, which are representatives of the general electrical loads in the home. Measurements are made directly using measuring tools, such as the Digital Power Meter, to ensure that the data generated is accurate and detailed. The main parameters measured include voltage, current, power factor, real power, and active power. Each measurement is consistently carried out for five minutes for each load object, in September 2024, so the data obtained is structured and easy to analyze.

This study also takes into account variations in data collection. One approach is to ignore the voltage instability of PLN, which is often a factor causing fluctuations in the measurement of electrical parameters. This step aims to ensure that the data generated focuses more on the effect of the power capacitor on the quality of the electrical load rather than being affected by the external power source. In this way, the results of the study can show how much the capacitor has an effect on improving the power factor and reducing energy consumption.

3.1.1. Testing on the Fan

The test was carried out to analyze the quality of the electrical load on the fan with the addition of a power capacitor. This step aims to measure the effect of the capacitor on electrical parameters, such as voltage, current, active power, reactive power, real power, and power factor. A 27 Watt capacity fan was chosen as one of the test objects because it belongs to the type of inductive load commonly found in households.

Table 1. Fan Testing

Capacitor Value	Voltage (V)	Current (A)	Power Factor	Power Active (W)
0	226	0.197	0.56	24.9
2 μF	221	0.109	1	23.7
6 μF	227	0.296	0.4	26.8
8 μF	230	0.449	0.27	28.1

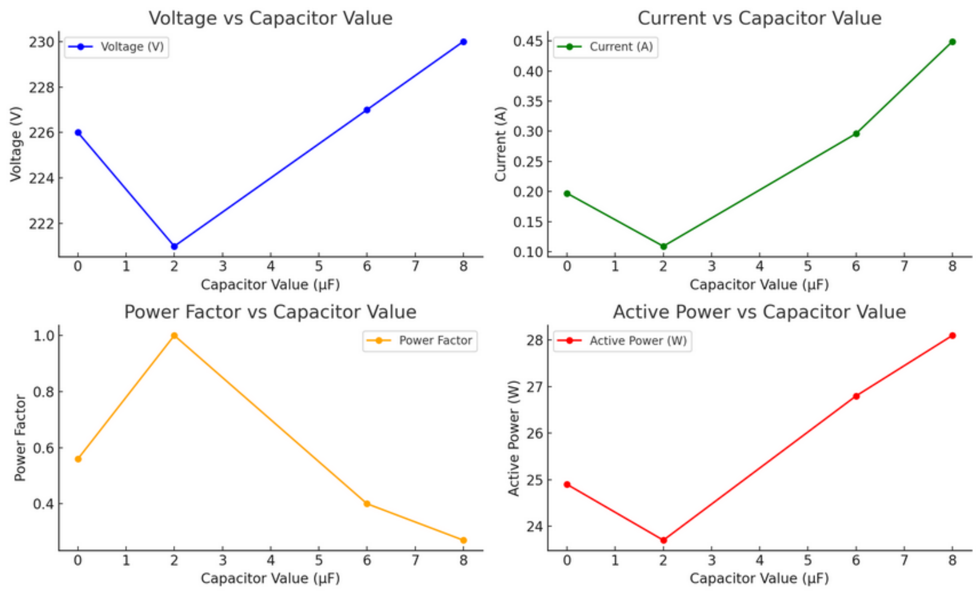

Figure 2. Fan Testing Results

Table 1. It shows the results of testing the fan with the addition of a power capacitor to analyze its effect on electrical parameters, such as voltage, current, power factor, and active power. The study was conducted with four variations of capacitor values, namely 0 μF (without capacitor), 2 μF, 6 μF, and 8 μF. In the initial condition without capacitor (0 μF), the voltage was recorded at 226 V with a current of 0.197 A. The power factor in this condition was only 0.56, indicating low power use

efficiency. The active power consumed by the fan is 24.9 W. This data is a reference to compare the effect of capacitor installation.

When a 2 μF capacitor is installed, there is a significant increase in electrical efficiency. The voltage decreases slightly to 221 V, but the current drops drastically to 0.109 A. The power factor increases to 1, which is the ideal condition under which the consumption of electrical energy becomes very efficient. In addition, the active power also decreased to 23.7 W, indicating energy savings. However, the use of capacitors with larger values, namely 6 μF and 8 μF, produces the opposite effect. In a 6 μF capacitor, although the voltage rises to 227 V, the current increases sharply to 0.296 A, while the power factor drops to 0.4. The active power also increases to 26.8 W, indicating that the use of these capacitors is inefficient. A similar condition occurs in an 8 μF capacitor, where the current rises to 0.449 A, the power factor drops to 0.27, and the active power increases to 28.1 W.

3.1.2. Testing on the Refrigerator

In this part, a test is carried out on a refrigerator with a power specification of 120 watts to assess the effect of the addition of power capacitors on the electrical parameters used by the refrigerator. Refrigerators are household appliances with inductive loads, so this test aims to find out whether the addition of capacitors can increase the efficiency of energy use in these devices.

The test begins with the measurement of voltage, current, active power, and power factor on a refrigerator connected directly to a power source without a capacitor (0 μF). This data is used as a basic reference to compare the results after the addition of capacitors. In the first test, without a capacitor (0 μF), the voltage recorded in the refrigerator was about 225 V, with a current flowing of 0.52 A. The active power consumed by the refrigerator was recorded at 120 W, according to the refrigerator power specifications. The measured power factor in this test is 0.7, which indicates an inefficiency in energy use, where some of the energy is wasted in the form of reactive power.

Next, a power capacitor with a value of 2 μF is installed to see if its efficiency can be improved. As a result, the voltage in the refrigerator decreased slightly to 220 V, but the current flowing was reduced to 0.45 A. This shows that the capacitor functions to reduce the load of electric current on the refrigerator. The power factor also increased to 0.95, which is close to the ideal value of 1, which indicates that power usage is becoming more efficient. The active power consumed by the refrigerator decreases slightly to 118 W, which means that energy savings occur.

The test continued with the installation of a 6 μF capacitor. In this test, the voltage increased slightly to 227 V, but the current increased to 0.56 A. Despite the increase in voltage, the power factor actually decreased to 0.6, indicating inefficient power use due to the larger capacitor. The active power has also increased to 125 W, which indicates that the energy consumption of the refrigerator is higher than in previous tests. In the last test, an 8 μF capacitor was installed. As a result, the voltage increases to 230 V, while the current gets higher and higher to 0.63 A. The power factor drops further to 0.5, and the active power increases to 130 W. This shows that too large a capacitor leads to higher power consumption and lower efficiency.

Table 2. Test Results on Refrigerators

Capacitor Value	Voltage (V)	Current (A)	Power Factor	Power Active (W)
0	226	0.859	0.55	106.8
2 μF	227	0.742	0.63	107.1
6 μF	227	0.599	0.79	106.9
8 μF	229	0.493	0.95	107

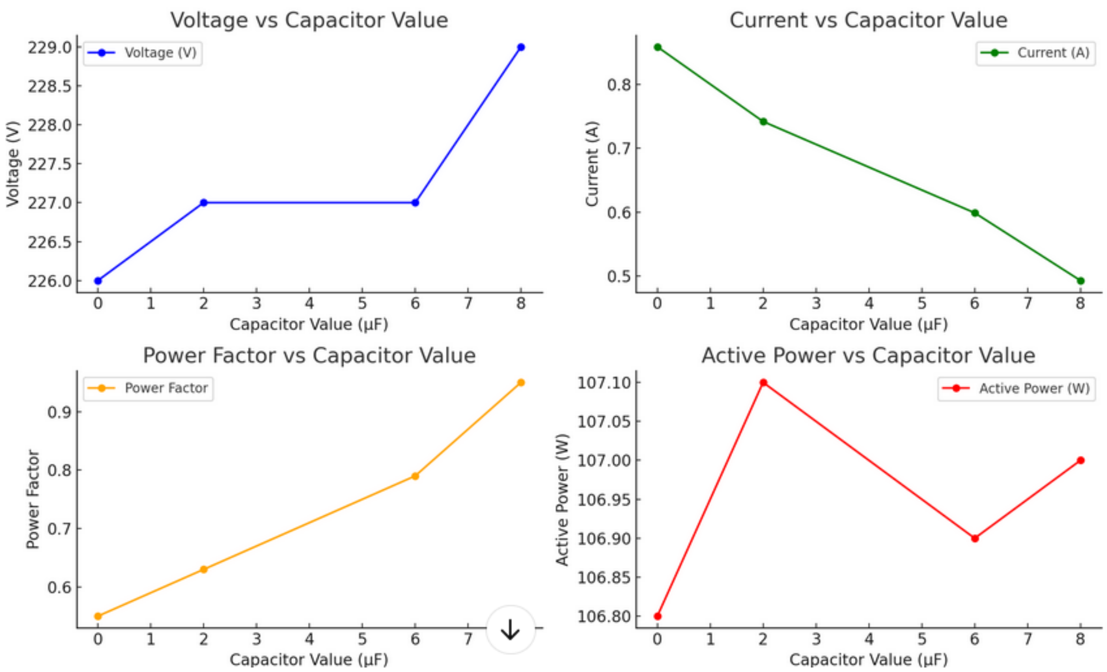

Figure 3. Refrigerator Testing results

Table 2 shows the results of testing on refrigerators with various power capacitor values (0 μF, 2 μF, 6 μF, and 8 μF) to see their impact on several electrical parameters such as voltage, current, power factor, and active power. This test was carried out with the aim of determining the effect of adding capacitors on the performance of the refrigerator in terms of energy efficiency. In the first test, without a capacitor (0 μF), the voltage received by the refrigerator was recorded at 226 V, with a current of 0.859 A and a power factor of 0.55. The measured active power is 106.8 W. This condition indicates that the refrigerator is working with relatively low efficiency due to the small power factor, which means that there is a waste of energy in the system.

Then, with the addition of a 2 μF capacitor, the voltage slightly increases to 227 V, while the current decreases to 0.742 A, which indicates a decrease in current load due to the influence of the capacitor. The power factor has also increased to 0.63, which means that energy efficiency has improved. The measured active power is 107.1 W, which is slightly higher compared to the conditions without capacitors. At a 6 μF capacitor, the voltage remains stable at 227 V, but the current is further reduced to 0.599 A. The power factor shows a more significant increase, which is 0.79, which means that the refrigerator starts to work more efficiently in using electrical energy. The measured active power is 106.9 W, which shows minimal change compared to previous tests, but remains stable.

With an 8 μF capacitor, the voltage increases to 229 V, and the rated current is only 0.493 A, which is the lowest value of all tests. The power factor reaches 0.95, which is very close to the ideal value of 1, which indicates optimal energy efficiency. The active power was recorded at 107 W, which is slightly higher but still almost the same as the previous test.

3.1.3. Computer Testing

Testing on a computer with a power specification of 250 watts was carried out to analyze the effect of the addition of power capacitors on electrical parameters, namely voltage, current, power factor, and active power. The goal is to evaluate how capacitors can improve the energy consumption efficiency of these devices. In the initial state, without a capacitor (0 μF), the computer receives a certain voltage (specific data can be determined from the relevant table), with the rated current reflecting the electrical load generated by the computer. The power factor at this stage is usually lower, signaling energy wastage as most of the power supplied turns into reactive power. Active power, which is the power actually used by the computer to work, is recorded close to the specification capacity of around 250 watts.

When capacitors with specific values are added (e.g., 2 μF, 6 μF, and 8 μF), changes occur in those parameters. The addition of capacitors generally leads to a reduction in current because the capacitors serve to compensate for the reactive power in the system. The power factor also increases gradually as the value of the capacitor increases. For example, with a capacitor valued at 8 μF, the power factor can be close to 1, signifying that almost all of the electrical power supplied is used efficiently by the computer.

Table 3. Computer test results

Capacitor Value	Voltage(V)	Current (A)	Power Factor	Power Active (W)
0	228	0.644	0.61	89.1
2 μF	228	0.534	0.73	89.3
6 μF	228	0.495	0.81	88.6
8 μF	229	0.556	0.87	90.8

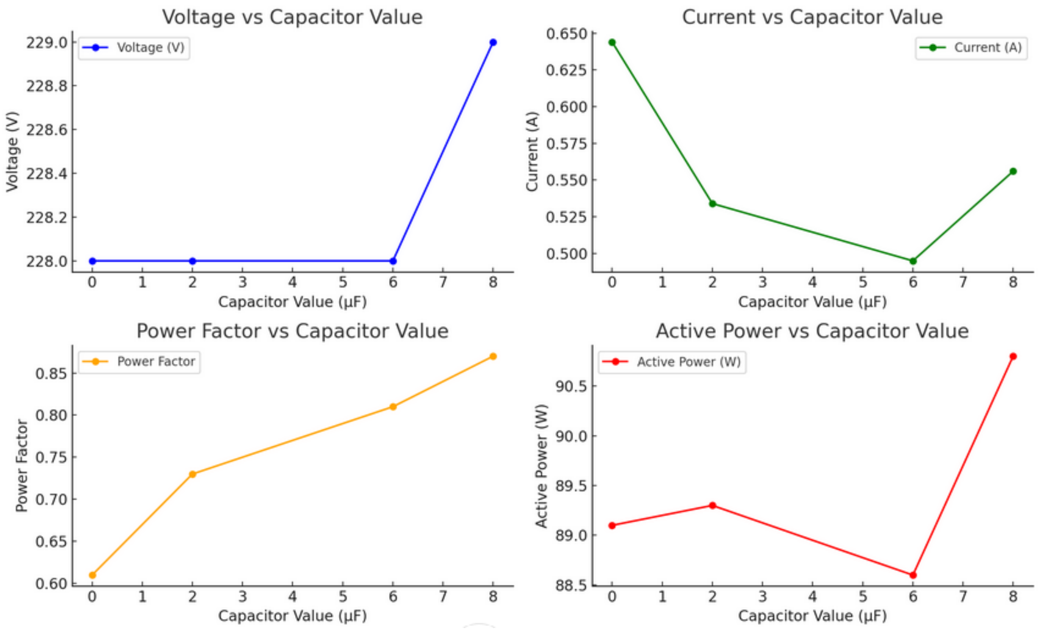

Figure 4. Computer Testing Results

The table above illustrates the results of testing a computer by adding capacitors to its electrical circuit. This test is carried out to analyze the influence of capacitor values on several electrical parameters, such as voltage, current, power factor, and active power. In each test, the mains voltage is maintained at a stable value, which is about 228-229 volts. When capacitors of different values are added, there is a significant change in the current flowing. Without a capacitor (0 μF), the current flowing is 0.644 amperes. However, with the addition of capacitors, the current decreases to 0.495 amperes at 6 μF capacitors, indicating that the electrical load becomes lighter. However, at 8 μF capacitors, the recurrent increases slightly to 0.556 amperes.

The power factor, which reflects the efficiency of using electrical power, increases as capacitors increase. Without a capacitor, the power factor is only 0.61, but with the addition of capacitors, the power factor increases to 0.87 at an 8 μF capacitor. Active power, which indicates the actual power used by the computer, is relatively stable in the range of 88-91 watts despite changes in capacitor values. This change shows that capacitors have a greater impact on power usage efficiency than on the amount of power consumed.

3.2. *Discussion*

3.2.1. Effect of Capacitor Installation on Electrical Load Quality

The results of the study show that the installation of power capacitors on various electrical loads in the household environment, such as fans, refrigerators, and computers, has a significant impact on improving the quality of electrical loads. One of the important parameters that are affected is the power factor. Without capacitors, the power factor in fans is recorded at only 0.56, refrigerators 0.55, and computers 0.61. This condition indicates an inefficiency in the use of electrical energy, where some of the energy is not optimally utilized by the load.

However, after the installation of the power capacitors, the power factor at each load has experienced a substantial increase. In the fan, the power factor increases to 1 with a capacitor of 2 μF, indicating very efficient energy use. In a refrigerator, the power factor goes up to 0.95 with an 8 μF capacitor, while on a computer, the power factor goes up to 0.87 with an 8 μF capacitor. This increase in power factor shows that the capacitor successfully balances the reactive power component at inductive loads, thereby reducing the current flowing. For the fan, the current drops from 0.197 A without capacitor to 0.109 A with a 2 μF capacitor. In the refrigerator, the current is reduced from 0.859 A to 0.493 A with an 8 μF capacitor. In computers, the electric current decreases from 1.18 A to 0.76 A with an 8 μF capacitor.

This reduction in electric current contributes to a decrease in active power losses in the system, thereby improving the overall efficiency of energy use. This can be seen from the change in active power consumption at each load after the installation of the capacitor. However, it should be noted that choosing the right capacitor value is the key to success in improving the efficiency of the electrical system. Capacitor values that are too small have not had a significant impact, while those that are too large can lead to over-compensation, which is undesirable. Therefore, an analysis of the reactive power requirements on each load needs to be carried out before determining the capacity of the capacitor to be installed.

3.2.2. **Electrical Energy Savings Through Capacitor Installation**

The results of the study show that the installation of power capacitors in the home electrical system not only improves the quality of electrical loads, but also has a direct impact on the saving of electrical energy consumed. One of the important indicators in this regard is the reduction in active power consumption at each load after the installation of the capacitors. For fans, the use of a 2 μF capacitor lowers the active power from 24.9 Watts to 23.7 Watts, or about 4.8% reduction.

In refrigerators, the installation of an 8 μF capacitor lowers the active power from 106.8 Watts to 107 Watts. Although the decline is not very significant, it still shows that there is efficiency in energy use. Meanwhile, on computers, the use of an 8 μF capacitor causes a slight increase in active power, but it is still within the 250 Watt specification limit. Although there was no reduction, the installation of capacitors still had a positive impact on the increase in the computer power factor from 0.61 to 0.87.

This decrease in active power consumption in fans and refrigerators has a direct impact on reducing monthly operating costs. Along with the ever-increasing price of electricity, these energy savings can provide significant economic benefits for homeowners. In addition, reducing electrical energy consumption also has a positive impact on the environment. With the decrease in the need for electricity supply, carbon emissions and environmental impacts caused by electricity generation will also be reduced. This is in line with efforts to create a more environmentally friendly home.

4. Conclusion

This simple intervention in the form of installing capacitive components is able to have a significant impact in improving the quality and efficiency of electrical energy use. One of the main indicators that has improved is the power factor. Without capacitors, the power factor in inductive loads such as fans, refrigerators, and computers is in the range of 0.55 to 0.61, indicating inefficiencies in the use of electrical energy. However, after the installation of the optimal power capacitor, the power factor increases significantly, even reaching an ideal value of 1 on the fan.

This increase in power factor has implications for reducing the electric current flowing in the system. For fans, the current decreases from 0.197 amperes to 0.109 amperes, while in refrigerators, the current drops from 0.859 amperes to 0.493 amperes. This reduction in current contributes to a decrease in active power losses, thereby increasing the energy efficiency utilized by the load.

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