Analysis of the Effect of Capacitor Storage Insertion Using Fuzzy Methods

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ABSTRACT

The insertion of capacitors in the power distribution system is one of the effective solutions to improve voltage quality, reduce power losses, and improve the operational efficiency of the power grid. This study aims to analyze the effect of capacitor insertion in the electrical system using the fuzzy method, which focuses on determining the optimal location and size of the capacitor. The fuzzy method was chosen because of its ability to handle uncertainty and variability in electrical system parameters, such as bus voltage and Power Loss Index (PLI). The results showed that by using the fuzzy method, the location and size of the capacitor can be determined more precisely, resulting in an increase in the voltage on the bus that previously decreased, as well as a significant reduction in active and reactive power losses. The reduction in active power losses reached 4.868% and reactive power losses reached 5.973%. The insertion of capacitors optimized by the fuzzy method has proven effective in improving the stability, efficiency, and reliability of the power distribution system, and can be used as a solution to reduce power losses in the electrical system.

Keywords: Capacitor Insertion, Fuzzy Method, Power Distribution System, Power Loss Index (PLI), Stability.

Introduction

The increasing demand for reactive power supply due to the growth of inductive loads is one of the main challenges in managing the electrical system. Inductive loads, such as electric motors, cause significant reactive power losses due to the lagging current phenomenon that affects system performance (Zhang et al., 2016). This load requires a solution to optimize power distribution, increase efficiency, and maintain power quality and voltage stability in the electric power distribution system (Sundararajan & Soni, 2018).

Along with the rapid development of electrical technology, especially in distribution systems, it is important to continue to improve the efficiency and reliability of the electrical system in order to be able to face the dynamics of loads and disturbances that can affect the performance of the distribution network (Sundararajan & Soni, 2018). One of the commonly applied solutions is the use of capacitors to compensate for the reactive power required by inductive loads, with the aim of improving the power factor and reducing power losses (Mohan et al., 2003).

Capacitor storage plays a key role in reducing power losses and maintaining voltage stability. However, capacitor management requires a more adaptive approach, considering the variability and uncertainty in load conditions and distribution networks (Abdel-Magid et al., 2005). One method that can be used to overcome this problem is *fuzzy logic* . This method allows the determination of the optimal capacitor storage capacity based on various parameters, such as voltage, load, and line conditions, by overcoming the uncertainty and complexity present in the distribution system (Zadeh, 1965). In addition, the phenomenon of voltage surge wave propagation caused by disturbances or sudden changes in the power network also affects power quality. Changes in the shape of these waves can cause detrimental distortions in the electrical system (Bollen, 2000). Therefore, it is important to understand how capacitors and other components can affect the propagation of these waves and their impact on power quality in the electrical system (Hughes, 2017).

In addition, low R/X ratio in distribution systems can lead to increased power losses and unacceptable voltage drops. Increased reactive power consumption results in higher network currents, potentially causing about 13% of the total power generated to be lost as line losses (Liu et al., 2014). One effective way to reduce these losses is to optimize the use of capacitors. Proper capacitor installation can reduce the current flowing in the conductors, thereby reducing power losses and voltage drops in the system (Naderi et al., 2016).

Various methods have been used to solve the problem of capacitor placement in distribution networks. Some artificial intelligence methods, such as genetic algorithms and fuzzy logic, have been shown to be efficient in optimizing capacitor placement (Talej et al., 2018). A combination of fuzzy logic and genetic algorithm methods, for example, has been adapted to obtain better results in determining the optimal size and location of capacitors (Chien et al., 2017).

This study aims to analyze the optimal placement and size of capacitors using a combination of fuzzy logic and genetic algorithm methods. This study will be conducted using MATLAB R2016b software to explore how both methods can improve efficiency, stability, and power quality in power distribution systems. It is expected that the results of this study can contribute to the development of more efficient adaptive methods for capacitor management in power distribution systems.

Formulation of the problem:

1) How to determine the optimal location and value of capacitors to be inserted into a distribution system.
2) How the insertion of capacitor storage affects the stability, reliability and efficiency of the system also needs to be understood thoroughly.
3) How to analyze the effect of capacitor storage using fuzzy methods in the context of power distribution systems.

LITERATURE REVIEW

1. Reactive Power in Electrical Systems

Reactive power is a power component that does not do real work but is needed to maintain the magnetic field in inductive loads, such as electric motors, transformers, and other inductive equipment. Increased reactive power consumption caused by inductive loads can result in power losses and voltage drops in the distribution system (Zhang et al., 2016). Inductive loads cause the current to lag behind the voltage, which results in decreased efficiency of the electrical system. Therefore, reactive power management is very important in maintaining power quality and voltage stability in the electric power distribution system (Sundararajan & Soni, 2018). Reactive power storage with capacitors is used to offset the need for this reactive power. Capacitors can generate the reactive power needed by inductive loads, thereby reducing the reactive power losses that occur in the distribution system. Proper capacitor insertion can improve the power factor, reduce power losses, and maintain stable voltage throughout the distribution system (Mohan et al., 2003).

2. Capacitor Management in Distribution Systems

One of the major challenges in managing an electrical system is the optimal placement and sizing of capacitors. Improper placement of capacitors can overload the system and reduce efficiency. Therefore, efficient capacitor management requires an adaptive and well-planned approach. Several methods used to optimize capacitor placement in a distribution network involve various techniques, such as genetic algorithms (GA), fuzzy logic, and a combination of both (Chien et al., 2017; Talej et al., 2018).

3. Fuzzy Logic Method in Capacitor Management

Fuzzy logic is a method used to handle uncertainty and complexity in decision making, especially in non-linear and uncertain systems. In the context of capacitor management, fuzzy logic can help determine the optimal size and location of capacitors by considering various distribution system parameters, such as voltage, current, and power factor (Zadeh, 1965). This method also allows to accommodate variations and uncertainties in load conditions and distribution networks that can change dynamically.

The application of fuzzy logic in capacitor management aims to improve power distribution efficiency, reduce power losses, and maintain voltage stability. For example, Jang (1993) developed a fuzzy-based control system for capacitor regulation that allows automatic adjustment to changing system conditions.

4. Genetic Algorithm in Capacitor Placement Optimization

In addition to fuzzy logic, genetic algorithms (GA) have been widely used in research to find optimal solutions in capacitor placement. GA is a bio-inspired optimization method that uses the principle of natural selection to find the best solution. In capacitor placement, this algorithm can be used to explore various possibilities of capacitor placement and size in a distribution system, considering the objectives of minimizing power losses, increasing power factor, and maintaining voltage within permissible limits (Talej et al., 2018). The application of GA in capacitor placement involves representing solutions in the form of chromosomes, which are then processed through selection, crossover, and mutation operators to produce the best solution. One of the main advantages of using GA is its ability to solve complex optimization problems with many variables and constraints.

5. Combination of Fuzzy Logic and Genetic Algorithm

The combination of fuzzy logic and genetic algorithm methods has been studied in several studies to optimize capacitor placement. The combination of these two methods can provide a more flexible and efficient solution to optimization problems, because GA can be used for global solution exploration, while fuzzy logic can be used to handle uncertainty in the system and decision making based on uncertain rules (Chien et al., 2017; Jang, 1993). Studies that combine these two methods show that the combination of GA and fuzzy logic can provide better results in optimizing capacitor placement, especially in terms of reducing power losses, increasing distribution efficiency, and maintaining voltage stability in the distribution network (Talej et al., 2018). This method is also more adaptive to changing system conditions.

6. Effect of Capacitor Insertion on Power Quality

The insertion of capacitors in the power distribution system can affect the power quality, especially in terms of voltage wave distortion. The phenomenon of voltage surge wave propagation, caused by disturbances or sudden changes in the power network, can affect the voltage waveform and cause distortion in the system. Proper placement of capacitors can help reduce this distortion and improve the power quality in the system (Bollen, 2000; Hughes, 2017). Capacitors function to stabilize voltage, reduce fluctuations, and improve the quality of voltage waves used by electrical equipment. Therefore, it is important to consider the impact of capacitor insertion on power quality, especially in terms of reducing voltage surge wave distortion that can damage electrical equipment or cause damage in the distribution system (Hughes, 2017).

Research Method

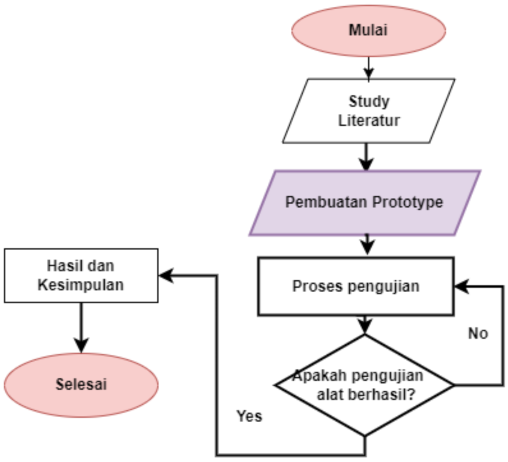

Figure 1. Flowchart

The following is a flowchart description:

1) Start: The starting point of the process.
2) Literature Study: Conducting research and reviewing relevant literature to understand theoretical background or gather information.
3) Prototyping: Designing and developing a prototype based on literature studies and the problems encountered.
4) Process: Testing or analyzing prototypes through experiments or practical applications.
5) Was the Tool Testing Successful?
6) Decision point: If “Yes”, proceed to Results and Conclusions.
7) If “No”, go back to “Prototyping” to refine the design or approach.
8) Results and Conclusions: Based on successful testing, analyze the data and summarize the results.
9) Done: The process ends here.

Results and Discussion

The MATLAB application is a tool designed to support the implementation, analysis, and simulation of fuzzy logic-based systems. This toolbox provides a graphical interface and built-in functions to simplify the process of developing fuzzy logic models, including fuzzification, inference, and defuzzification.

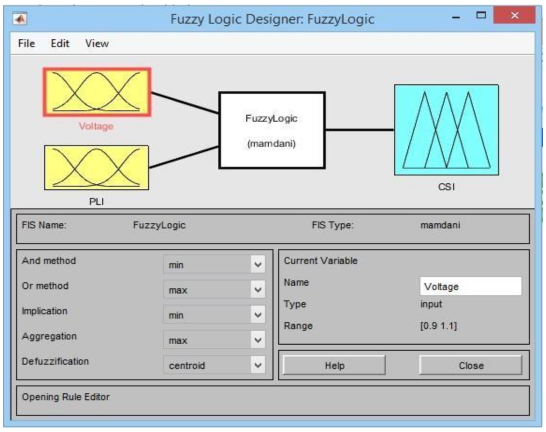

Figure 2. Fuzzy Logic *Toolbox* Display in Matlab R2016b

1. Power Flow Before Capacitor Placement

The power flow calculated using the Newton-Raphson method is the initial step to obtain the voltage results at each bus and losses in the line. Based on the power flow results, it was found that there were 8 buses that had voltages below 1 pu, namely buses 6, 9, 10, 11, 12, 13, 14, and 15. After analyzing the power flow, the optimal capacitor location and size can be determined using the fuzzy logic method and genetic algorithm.

2. Determining Capacitor Location with Fuzzy Logic

Determining the location of the bus that is a candidate for capacitor placement is done using the fuzzy logic method. The input of this fuzzy logic is the voltage on the bus and the Power Loss Index (PLI), while the output produced is the Capacitor Suitability Index (CSI). The PLI value is calculated based on the available equation and the results are shown in Table 2.

Table 1. PLI (Power Loss Index) Calculation Results for each Bus

No	Bus	Power Loss (MW)	Voltage (pu)	PLI
1	1	496,662	1,050	1.0000
2	2	174,800	1,000	0.5030
3	3	181,400	1,000	0.5132
4	4	253,300	1,000	0.6242
5	5	-48,000	1,045	0.1590
6	6	-116,000	0.987	0.0540
7	7	-142,000	1,038	0.0138
8	8	-84,500	1,034	0.1026
9	9	-106,000	0.982	0.0694
10	10	-98,000	0.964	0.0818
11	11	-30,000	0.945	0.1868
12	12	-109,000	0.930	0.0648
13	13	-67,000	0.971	0.1296
14	14	-151,000	0.965	0.0000
15	15	-92,000	0.969	0.0910
16	16	-31,520	1,036	0.1845

The results of the Power Loss Index (PLI) calculation on each bus show that buses with higher PLI values have larger capacitor requirements. Based on these results, buses with higher

PLI will be the main candidates for capacitor placement to improve power distribution and reduce power losses.

Table 2. Fuzzy Logic Results

Bus (No.)	Voltage (pu)	PLI	CSI
1	1,050	1.0000	0.2520
2	1,000	0.5030	0.2540
3	1,000	0.5132	0.2680
4	1,000	0.6242	0.3740
11	0.945	0.1868	0.2520
12	0.930	0.0648	0.3380

The output results of the fuzzy logic displayed in Table 3 show the Capacitor Suitability Index (CSI) values for each bus. Based on the CSI calculation results, bus 11 and bus 12 are determined as candidate buses for optimal capacitor placement, with CSI of 0.2520 and 0.3380, respectively. This is due to the voltage on both buses being below the tolerance limit of ±5%, as well as the CSI value being greater than 0.25.

Meanwhile, although bus 1 (CSI = 0.2520), bus 2 (CSI = 0.2540), bus 3 (CSI = 0.2680), and bus 4 (CSI = 0.3740) have CSI values greater than 0.25, they are not selected because the voltages on these buses are still within the tolerance limit of ±5%. In addition, buses 1 to 4 are slack buses (reference buses) and generator buses, which do not require capacitors. Therefore, only buses 11 and 12 are selected as candidates for optimal capacitor placement.

3. Optimal Capacitor Size Testing with Genetic Algorithm.

Capacitor sizing testing was performed using a genetic algorithm run four times, entering the following parameters:

- Population size
- Maximum generation
- Crossover rate
- Mutation rate

Determination of genetic algorithm parameters using Trial and Error techniques, which involve experimenting with several combinations of these parameters. Table 4 shows the test results for the optimal capacitor size based on the results of genetic algorithm simulations. Table 4 (which is not yet available) can contain simulation results showing the optimal capacitor value obtained based on the genetic algorithm, including information such as the number of populations used, the maximum number of generations, and the chances of crossover and mutation.

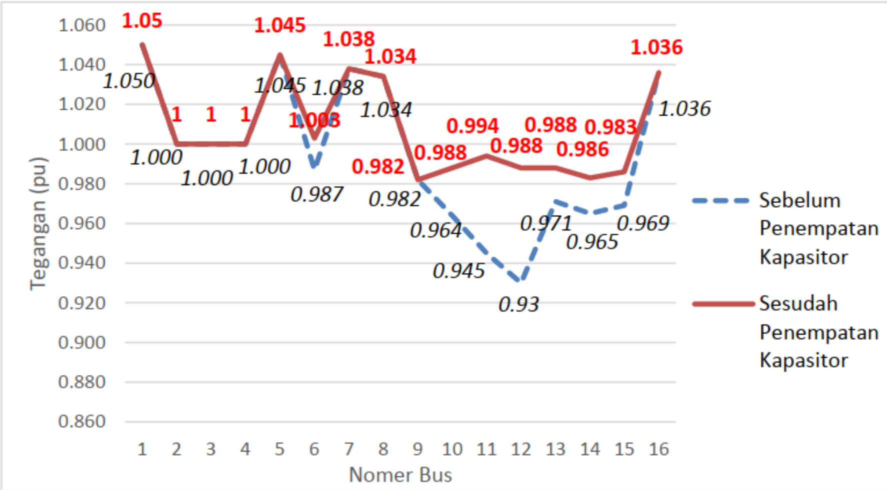

Figure 3. Voltage Before and After Optimization

Based on the results shown in Figure 8 and Figure 9, the decrease in active and reactive power losses in the electrical system after the placement of capacitors can be explained. The decrease in active power losses (MW) occurred in several transmission lines, such as lines 1-6, 6-10, 11-12, 3-13, and 13-14. This shows that the placement of capacitors can reduce active power losses in these lines. Capacitors function to improve the power factor and reduce the current in the line, which in turn reduces the active power losses caused by resistance in the transmission line. Before the placement of capacitors, the total active power losses reached 31,142 MW, and after the placement of capacitors, the total active power losses decreased to 29,626 MW, which means a decrease of 4,868%. Although this decrease is significant, its impact is still limited.

In addition, a decrease in reactive power losses is also seen in lines such as 1-6, 6-10, 11-12, and 3-13. Capacitors help correct the power factor by providing reactive power, which reduces the reactive power losses in the transmission line. Before the placement of capacitors, the total reactive power loss was 128,859 MVar, and after the placement of capacitors, the total reactive power loss decreased to 121,162 MVar, with a decrease of 5.973%. Although this decrease is quite good, the reduction is not too large, which may be due to some lines not being affected by the placement of capacitors or the capacitors used are not large enough to have a significant impact on all lines.

Overall, capacitor placement has successfully reduced active and reactive power losses, although the effect is not too large. Several factors that affect the effectiveness of capacitor placement include the limited location of capacitor placement on buses with a CSI of more than 0.25, limited capacitor capacity, and transmission network conditions that affect power losses on the line. Therefore, to increase the effectiveness of reducing power losses, adjustments to the capacitor size or placement of additional capacitors in other more optimal locations may be required.

4. Effect of Capacitor Storage Insertion on System Stability, Reliability, and Efficiency

The insertion of capacitors in the electrical system has a significant effect on the stability, reliability, and efficiency of the power distribution system. In general, the insertion of capacitors aims to improve the power factor and reduce power losses in the transmission line. The following is an analysis of its effects on each aspect:

- System Stability: Inserting capacitors can improve the voltage at various buses in a distribution system. This is very important to maintain voltage stability in the electrical system, especially under fluctuating load conditions. With capacitors installed at strategic points, the system becomes more resistant to disturbances that can cause unwanted voltage drops. In addition, capacitors can help reduce frequency and voltage oscillations, which play a role in maintaining the stability of the overall electrical system operation.

- System Reliability: The reliability of a power distribution system is greatly influenced by the availability of stable reactive power. The insertion of capacitors at certain locations helps reduce the need for reactive power to be supplied by the generator, thereby minimizing the possibility of a shortage of reactive power that can cause disruptions. In this way, capacitors help maintain a balance between active and reactive power in the system, which improves the operational reliability of the distribution system.
- System Efficiency: The insertion of capacitors serves to reduce power losses in transmission lines, especially reactive power losses. Power losses occur due to the presence of inductive components in the line that inhibit the flow of power. With capacitors providing local reactive power, the current flowing in the transmission line becomes more efficient, so that power losses can be reduced. This efficiency is also related to the reduction of loads on generators and transmission lines, which reduces losses due to resistance and increases the efficiency of energy distribution.

5. Analysis of the Effect of Capacitor Storage Using Fuzzy Method in the Context of Power Distribution Systems

Fuzzy methods play an important role in determining the optimal placement and size of capacitors in a power distribution system. In this case, fuzzy logic can be used to consider various variables that affect the performance of the electrical system, such as bus voltage and power loss index (PLI). With this approach, the analysis of the effect of capacitor insertion becomes more flexible and accurate, considering the many factors that must be considered in the planning and operation of the distribution system.

- Capacitor Placement Location Determination: The fuzzy method allows to determine the capacitor location by considering variables such as bus voltage and Power Loss Index (PLI) on the distribution buses. Fuzzy logic produces an output in the form of Capacitor Suitability Index (CSI), which is used to select the most suitable bus for capacitor placement. With this method, a more accurate analysis can be done to determine buses with low voltage and high power loss that need to be given capacitors to improve the performance of the distribution system.
- Capacitor Size Optimization: Once the capacitor locations are determined, fuzzy methods can also be used to optimize the capacitor sizes required for each bus. In this case, fuzzy logic helps to consider various factors such as voltage tolerance limits, required reactive power capacity, and power losses. With this approach, the optimal capacitor size can be selected to achieve a good balance between reducing power losses, improving power factor, and adjusting voltages throughout the system.
- Impact on System Performance: By using fuzzy methods, the analysis can be more detailed and consider the uncertainty and variability of network conditions, such as load fluctuations and voltage changes. This allows for more adaptive capacitor placement, which directly affects the performance of the power distribution system. Decisions resulting from fuzzy methods are more acceptable in the context of complex and dynamic systems, because fuzzy logic is able to handle uncertainty and provide more robust solutions.

Overall, the insertion of capacitors using the fuzzy method improves the performance of the power distribution system in a more structured, accurate, and adaptive manner to changing system conditions. Thus, in terms of efficiency, stability, and reliability, the use of capacitors in a power distribution system supported by the fuzzy method provides significant benefits.

Conclusion

The insertion of capacitors in the power distribution system has a positive impact on the stability, reliability, and operational efficiency of the electrical system. In particular, capacitors can help improve bus voltages, reduce active and reactive power losses, and improve the balance between active and reactive power. This contributes to voltage stability, reduced operational disturbances, and increased power distribution efficiency.

In capacitor insertion analysis using fuzzy method, this approach allows to determine the optimal location and size of capacitors by considering various factors such as bus voltage, Power Loss Index (PLI), and other network conditions. Fuzzy method helps in dealing with uncertainty and variability in the power distribution system, so that the resulting decision is more accurate, adaptive, and robust. Overall, the combination of capacitor insertion and the use of fuzzy method in power distribution analysis has proven effective in increasing system efficiency, reducing power losses, and improving the reliability and stability of the overall electrical system operation.

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