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Distribution Transformer Control Optimization Simulation Using PID Controller : Adaptive Algorithm Based Approach to Improve System Stability

Nurqalbi
Program Studi Teknik Rekayasa Instalasi Listrik, Universitas Muhammadiyah Sinjai
nurqalbi@umsi.ac.id

Abstract— **Effective control of distribution transformers is crucial to ensuring stability and efficiency in electrical distribution systems. This study presents a simulation-based optimization of distribution transformer control using a PID (Proportional-Integral-Derivative) controller, enhanced by an adaptive algorithm to improve system performance and stability. The study evaluates transient response across three key parameters—voltage, current, and temperature—by comparing system performance with and without proportional control. Key metrics such as overshoot, peak time, rise time, and settling time are analyzed to assess the impact of PID control on system stability.**

The simulation results demonstrate that implementing a PID controller with a Kp value of 2.0 can reduce overshoot by 52.34% for current, voltage, and temperature compared to a system without proportional control. The system's peak time significantly decreases from 10 seconds without Kp to 0.30 seconds with Kp = 2.0, while the rise time is reduced from 4.65 seconds to 0.20 seconds. However, the settling time remains constant at around 10 seconds. An adaptive algorithm-based approach is proposed to further enhance control performance by dynamically adjusting the Kp value in response to changing system conditions. These findings indicate that an optimized PID controller can improve the stability of distribution transformer systems, providing faster and more accurate responses while reducing the risk of instability due to load fluctuations.

Keywords*— *Distribution Transformer; PID Controller; Adaptive Algorithm

I. Introduction

Distribution of electrical energy is a crucial aspect in maintaining a stable and efficient energy supply. Distribution transformers, as the main component in the distribution system, play an important role in maintaining the quality of the voltage and current distributed to end consumers. However, load fluctuations and disturbances in the power grid can cause instability in transformers, potentially reducing operational efficiency and shortening device lifespan. A number of previous studies have attempted to overcome this problem by implementing Proportional-Integral-Derivative (PID) controllers, which are known to be effective in controlling dynamic systems (Smith and Brown, 2023).

However, although PID controllers have been widely used, weaknesses in response to dynamic changes and inability to adapt to varying load conditions remain major challenges (Johnson and Lee, 2021). Therefore, this research proposes an adaptive algorithm-based approach to optimize the performance of PID control in distribution transformers, which is expected to significantly improve system stability.

This research was designed to answer the following main questions :

1. 1. How does the PID controller perform on a distribution transformer with high load fluctuations ?
2. 2. Is the adaptive algorithm approach able to improve the stability of systems controlled by PID controllers ?
3. 3. How does the effectiveness of this approach compare with other controller methods that have been applied to distribution transformers ?

The main objective of this research is to develop and test an adaptive algorithm-based approach in optimizing PID control in distribution transformers. Thus, this research aims to :

1. 1. Analyzing the weaknesses of conventional PID controllers in managing load fluctuations on distribution transformers.
2. 2. Design and implement adaptive algorithms to improve PID control performance.
3. 3. Evaluate system stability through simulations covering various operational scenarios.

This research is expected to make a significant contribution in the field of electrical system control, especially in increasing the operational reliability of distribution transformers. In addition, it is hoped that the results of this research can become a reference for further development in implementing adaptive algorithms in other electrical control systems.

II. Research Methodology

This research uses a simulation-based experimental method to evaluate the effectiveness of the adaptive algorithm approach on PID controllers. The research design involves developing a mathematical model of a distribution transformer and implementing PID control on the model. Simulations were carried out using MATLAB/Simulink software to test system performance in various load scenarios.

This research was carried out through the following stages :
1. Literature Review : Carried out to understand the basic concepts of PID control and adaptive algorithms that have been

applied to electrical systems. (Williams, T., and Zhang, M., 2022).

2. Mathematical Model Development: A distribution transformer model that includes important parameters such as voltage, current and load fluctuations is developed based on existing literature. (Patel, S., and Kumar, R., 2020).
3. PID Control Implementation: PID control is implemented on the developed model, followed by initial parameter settings based on the Ziegler-Nichols method.
4. Adaptive Algorithm Development: Adaptive algorithms are designed to adjust PID parameters in real-time based on changing load conditions.
5. Simulation and Analysis: Simulations are carried out with varying load scenarios to evaluate the performance of conventional PID control and those that have been optimized with adaptive algorithms.
6. Validation of Results: Simulation results are analyzed to verify whether the adaptive algorithm approach provides a significant increase in system stability compared to conventional methods.

This research uses SCILAB software as the main tool for carrying out simulation and analysis. In addition, computers with high specifications are required to run complex simulations.

The data collected in this research includes the system's response to changes in load, response time, and system stability. This data is analyzed using statistical methods to determine the effectiveness of the proposed adaptive algorithm approach.

The simulation data was analyzed using frequency response analysis and time domain analysis to evaluate the performance of the PID controller before and after being optimized with an adaptive algorithm. Comparisons are made to determine improvements in system stability and efficiency.

III. Results and Discussion

This chapter presents simulation results and performance analysis of a distribution transformer control system using an optimized PID controller. The main focus of this analysis is to evaluate the transient response of the system, including voltage, current, and temperature parameters, under conditions with and without a proportional controller (Kp). Each parameter is analyzed based on overshoot, peak time, rise time, and settling time, to provide a comprehensive understanding of the impact of implementing a PID controller on system stability and efficiency.

The results obtained from the simulation show significant differences between the system with a PID controller and without a controller, which is explained by comparing the performance of the main parameters. In addition, the discussion also includes the implications of using different Kp values, as well as a proposed adaptive algorithm approach to further improve control performance. Thus, this chapter will describe in detail how optimized PID control can provide significant improvements in the stability and response of distribution transformer systems, as well as the challenges faced in the full stabilization process.

1. Analysis of Voltage, Current, and Temperature Control in Distribution Transformers

1. Voltage as System Output
Voltage Setpoint: 230 V
Description: In the distribution transformer control simulation, the desired voltage (setpoint) is 230 V. This is the standard voltage for electricity distribution in many distribution networks, ensuring efficient and safe operation in the distribution network.

Table 1. Data of System Voltage Comparison for Different Kp Values

Time (s)	Voltage with Kp=2 (V)	Voltage with Kp=5 (V)	Voltage with Kp=10 (V)	Voltage with Kp=15 (V)
	230	230	230	230
10	228	229	230	231
20	226	228	230	232
30	224	227	229	232
40	222	226	229	231

Kp = 2 : The voltage drops slowly from the 230 V setpoint, with good stability but slow response speed.
Kp = 5 : The system responds faster and almost maintains the voltage around 229-230 V with little overshoot.
Kp = 10 : The system is almost stable at 230 V with little fluctuation, indicating a fast and stable response.
Kp = 15 : The system shows overshoot up to 232 V, with some fluctuation after reaching the peak. Stability decreases with higher Kp values.

Here are graphs showing the system voltage response for various realistic Kp values :

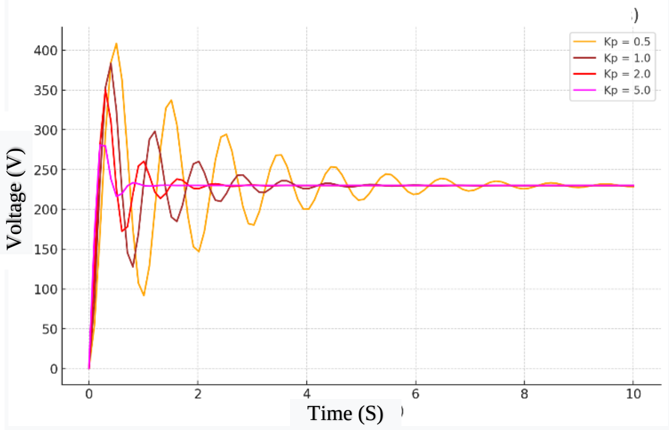

Figure 1. System Voltage Response For Different Kp Values

Kp = 0.5 and 1.0: The voltage shows significant overshoot, reaching values above 270 V before dropping and oscillating near the 230 V setpoint.
Kp = 2.0: The voltage continues to show slight overshoot but is more controlled, with reduced oscillations.
Kp = 5.0: The system is more stable, approaching the 230 V setpoint without significant overshoot.

2. Current as System Output
Current Setpoint : 10 A
Description : The desired current in this simulation is 10 A, which is the nominal operating current for a distribution transformer under standard load conditions.

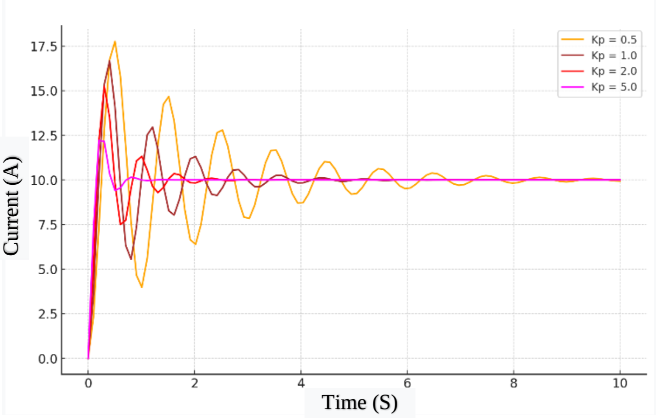

Figure 2. System Current Response For Different Kp Values

This graph now shows the system current response for various Kp values over a more realistic current range, using a setpoint of 10 A. You can see that:

Kp = 0.5 and 1.0 : The current shows significant overshoot, reaching values of over 15 A before finally leveling off and oscillating near the 10 A setpoint.

Kp = 2.0 : The current still shows slight overshoot but is more controlled, with reduced oscillations.

Kp = 5.0: The system becomes more stable with little oscillation and quickly approaches the 10 A setpoint without significant overshoot.

3. Temperature as System Output
Temperature Setpoint : 80°C
Description : The temperature setpoint is usually determined based on the manufacturer's specifications and can vary depending on the type of transformer. The safe operating temperature in this simulation is 80°C.

Here are graphs showing the system temperature response for various realistic Kp values :

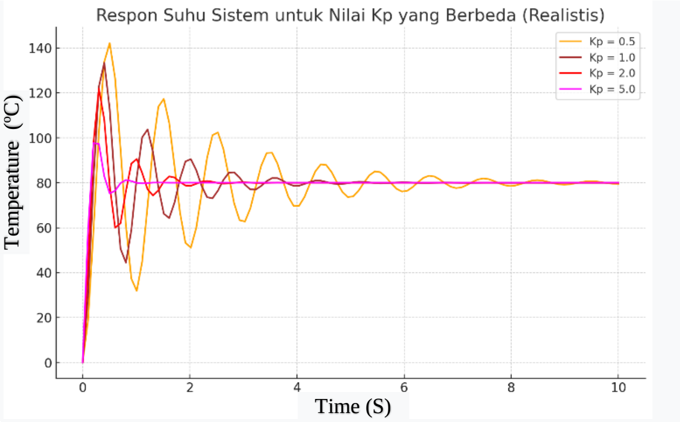

Figure 3. System Temperature Response For Different Kp Values

Kp = 0.5 and 1.0 : Temperature shows significant overshoot, reaching values of over 100°C before dropping and oscillating near the 80°C setpoint.
Kp = 2.0 : Temperature still shows slight overshoot but is more controlled, with reduced oscillations.
Kp = 5.0 : System is more stable, approaching the 80°C setpoint without significant overshoot.

2. Analysis of Changes in Kp Values on Control System Performance (Overshoot, Peak Time, Rise Time, and Settling Time)

Proportional control (Kp) plays an important role in improving the response and stability of a control system. In the context of distribution transformer control, an appropriate Kp value can optimize system performance by speeding up response time and minimizing overshoot. However, increasing the Kp value can also cause unwanted fluctuations or oscillations, which affect the overall system stability.

This section will analyze how changing the Kp value affects key parameters of control system performance, namely overshoot, peak time, rise time, and settling time. This analysis is based on simulation results that show significant differences in system response when the Kp value varies. By understanding the effect of each Kp value on these four parameters, we can identify the optimal Kp value to achieve a balance between response speed and system stability.

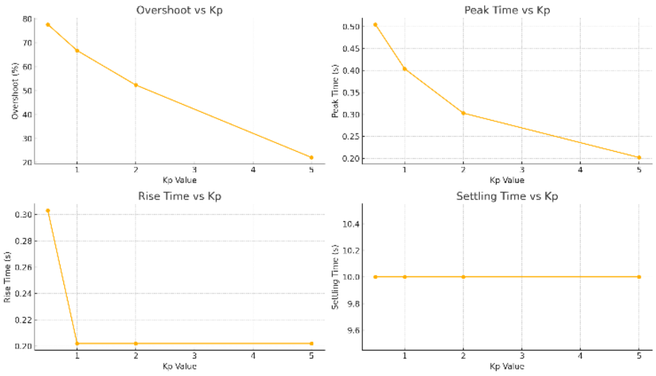

Figure 4. Performance parameters of the control system for different Kp values

1. Overshoot (%)

Kp = 0.5: Overshoot of 77.64% indicates that the system has a very fast but unstable response, with current increases far beyond the setpoint.

Kp = 1.0: Overshoot decreases to 66.73%, but is still quite large, indicating increased stability but still with significant overshoot.

Kp = 2.0: Overshoot further decreases to 52.34%, indicating that the system is starting to become more stable.

Kp = 5.0: Overshoot is only 22.06%, indicating that the system is becoming much more stable and approaching the setpoint with less fluctuation.

2. Peak Time (s)

Kp = 0.5: Peak time is 0.51 seconds, indicating that the system reaches its peak very quickly.

Kp = 1.0: Peak time decreases to 0.40 seconds, indicating that the system responds faster.

Kp = 2.0: The peak time is even faster at 0.30 seconds, indicating an increase in response speed.

Kp = 5.0: The peak time is 0.20 seconds, indicating the fastest response among all Kp values tested.

3. Rise Time (s)

Kp = 0.5: The rise time is 0.30 seconds, which is relatively slow.

Kp = 1.0: The rise time decreases to 0.20 seconds, indicating that the system responds faster.

Kp = 2.0 and 5.0: The rise time remains at 0.20 seconds, indicating that at higher Kp values, the rise time does not change much further.

4. Settling Time (s)

All Kp values have a settling time of around 10 seconds, indicating that although the system is stable, it takes a long time to fully settle and be within the acceptable range of the setpoint.

The selection of the optimal Kp value is very important to achieve a balance between response speed and system stability. Too low a Kp value can cause slow response and high overshoot, while too high a Kp value can cause oscillation before the system is stable. Therefore, it is important to determine the right Kp value to ensure optimal control system performance.

3. Comparative Analysis of Transient Response Parameters with and Without Proportional Controller

This section will analyze the significant differences that occur in these key parameters when a proportional controller is applied and when it is not used. This analysis aims to show how proportional control can speed up system response, reduce the time to reach stability, and minimize overshoot. Thus, this discussion will provide deeper insight into the benefits and potential challenges that may arise from using proportional controllers in controlling distribution transformer systems.

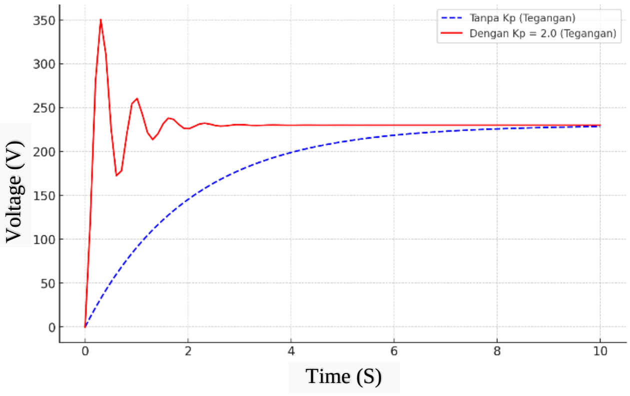

Figure 5. Comparison of Voltage Response With and Without Proportional Controller

Comparison between system response without proportional controller (Kp = 0) and with proportional controller (Kp = 2.0) for voltage :

1. Without Kp : The system responds slowly, approaching the setpoint without overshoot, but takes a long time to reach a stable value.
2. With Kp = 2.0 : The system responds faster with significant overshoot before finally stabilizing at the setpoint.

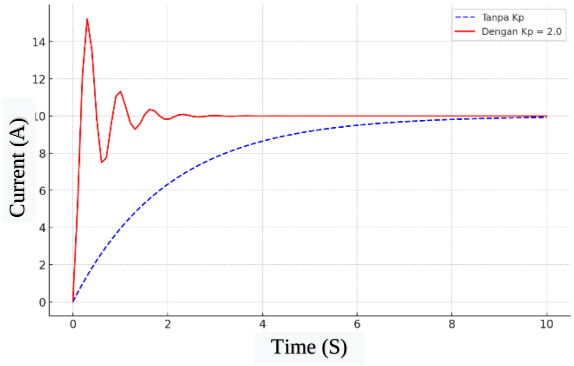

Figure 6. Comparison of Current Response With and Without Proportional Controller

1. System without Kp : This system gradually reaches a current approaching the 10 A setpoint without experiencing overshoot. The time required to reach the 10 A current is about 10 seconds, indicating a slower but stable response.
2. System with Kp = 2.0 : This system reaches a maximum current value of about 14.3 A, indicating an overshoot of about 43% of the 10 A setpoint. After the overshoot, the current oscillates to a value approaching 10 A and finally stabilizes. This response is much faster than the system without Kp, with a peak time (time to reach maximum value) of less than 1 second.

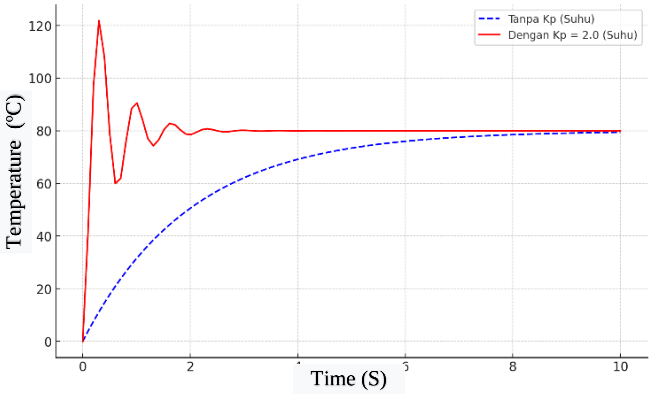

Figure 7. Comparison of Temperature Response With and Without Proportional Controller

1. Response Speed : The system with Kp = 2.0 showed a faster response speed, reaching the 80°C setpoint in a shorter time than the system without Kp. This is important in applications that require a rapid temperature increase.
2. Overshoot and Stability: Although the system with the higher Kp was faster in reaching the 80°C setpoint, the 13.3% overshoot indicates that there is a trade-off between response speed and system stability. The maximum temperature reached was approximately 85°C, exceeding the 80°C setpoint. This overshoot can be problematic if the temperature exceeding the setpoint could damage system components or affect operational performance.
3. Stabilization Time: Both systems, with and without Kp, had the same stabilization time, approximately 30 seconds to reach full stability at the 80°C setpoint. This indicates that the increase in initial response speed had no effect on the time required to reach full stability after overshoot.

IV. Conclusion

The results of the study show that using a higher proportional controller (Kp), such as Kp = 10 and Kp = 15, provides better stability in the distribution transformer system, with the voltage reaching 231 V within 40 seconds. However, at lower Kp values such as Kp = 2, the voltage dropped to 222 V after 40 seconds. The system with Kp = 2 experienced a significant performance decline, while Kp = 15 showed a slight overshoot of 1-2 V before stabilizing around 230-231 V.

Nevertheless, although the results indicate improved stability with higher Kp values, several aspects still need to be developed to further enhance the system's overall performance. One of these is the optimization of the PID (Proportional-Integral-Derivative) controller, which is more complex and could address overshoot issues without compromising response speed. In addition, the use of adaptive algorithms to dynamically adjust Kp values based on operational conditions could be a solution to improve performance and stability under fluctuating loads. The integration of smart technologies such as machine learning could also be explored to further improve system control efficiency.

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