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Power quality improvement in micro hydro power plant based-ELC and VSI using Fuzzy-PI controller

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Abstract

The stability of frequency and voltage in micro hydro power plants (MHPP) depends on the ability to maintain balance between active and reactive power while managing load variations. Active power is typically regulated by an Electronic Load Controller (ELC), while reactive power is managed by a Voltage Source Inverter (VSI), with the VSI specifically compensating for reactive power induced by inductive loads. This study aims to enhance the control of active and reactive power in an MHPP system under varying load conditions by improving the ELC and VSI using Fuzzy-PI controller. The Fuzzy-PI controller applied in the ELC ensures a more precise TRIAC firing angle, enabling accurate control of the ballast load to balance the active power. Similarly, Fuzzy-PI controller applied in the VSI provides precise reactive power compensation to counteract inductive load effects. The performance of the proposed Fuzzy-PI-based ELC and VSI was evaluated using a complete MHPP model simulated in Matlab. Results demonstrated that the improved ELC and VSI effectively enhanced the system performance. Specifically, the Fuzzy-PI controller enabled the ELC to achieve accurate active power balance, while the VSI delivered suitable reactive power compensation. Consequently, the system achieved improved frequency and voltage stability under load variations, leading to enhanced power quality in the MHPP.

1. Introduction

Micro Hydro Power Plant (MHPP) is an efficient renewable energy power generation and easy to operate [1]. MHPP system consists of water, turbine, and generator. When the water flow is constant as well as the electrical load power, the turbine will rotate constantly. The constant rotation of the turbine drives the generator to produce a constant frequency and voltage [2]. However, the electrical load power supplied by the MHPP is rather unstable, which might affect the frequency and output voltage of the generator. The frequency and voltage produced by the PLTMH must be kept constant [3]. Changes in active power of the MHPP system affect the frequency stability, while changes in reactive power influence the voltage stability. The frequency will decrease along with a decrease in the active power which occurs due to an increase in load power [4]. Then, a decrease in voltage occurs due to a decrease in reactive power caused by the increase of inductive loads [5]. Therefore, it is necessary to maintain the stability of the frequency and the output voltage of MHPP using Electronic Load Controller (ELC) and Voltage Source Inverter (VSI), respectively.

The ELC device includes a controlled rectifier and chopper circuit [6]. ELC plays a role in controlling the stability of active power using ballast loads to compensate for changes in load power to match the power produced by the generator [7]. In frequency regulation, ELC works by adjusting the TRIAC firing angle which controls the amount of current supplied to the ballast load [8]. The greater the load power that is compensated by the ballast load, the greater the TRIAC firing angle required. Then, the greater the TRIAC turning angle, the greater the harmonics will be in the PLTMH output voltage [9]. The precise setting of the TRIAC firing angle is required to optimize the ELC performance while eliminating harmonics when load changes occur. This can be achieved by implementing an appropriate control system scheme.

PI and PID controller are control schemes that have been widely applied in previous studies to improve the ELC performance [10,11]. The PI controller was able to recover the frequency with a fast rise time every time the load changes, but it causes overshoot and oscillation for a while before reaching the steady state. However, the D parameter of the PID controller was able to reduce the overshoot and oscillation well. Artificial Neural Networks (ANN) is also applied to ELC [12], with better results than PI or PID Controller. Meanwhile, fuzzy logic [13] was also developed and was able to recover the frequency with lower overshoot, but it still takes a long time to reach the steady state. The superiority of Fuzzy Logic over PI controller on ELC control under linear and non-linear load conditions has also been confirmed by researchers [14,15]. In addition, BFA-optimized fuzzy [16] and modified firefly algorithm [17] can also be an alternative control method to improve the ELC output, but it requires a rather long computational process. The combined control scheme between PI controller and fuzzy logic has also been confirmed for its good performance, however the tuning of PI parameters and fuzzy membership function values still have room for improvement [18] as well as for ANFIS-PI composition [19].

VSI is an additional device in micro-grid systems to provide reactive power to increase voltage level in the line, especially in the presence of inductive load [20]. VSI can be used to cover the limitations of Automatic Variable Regulator (AVR) in restoring voltage drops caused by changes of load power. VSI ensures the reactive power needed by inductive loads can be compensated following the changes of load power [21]. However, in MHPP system control, the use of VSI has not been widely considered as an important device. In practical, VSI circuit is normally installed as a single device or combined with other devices, such as SVC, STATCOM, etc. and managed by various control strategies [22]. PI and PID controllers have been the basic controllers applied to VSI circuit [23-25]. Fuzzy logic control has also been frequently implemented as single fuzzy logic or combined with ANN [26,27]. A combination of PI controller and fuzzy logic has also been developed to improve the performance of standalone PI or fuzzy logic [28,29]. Robust controllers have also been designed to have more robust output for VSI, such as H_∞ and SMC [30,31]. However, most of the proposed controllers have not been prepared for the MHPP system.

This study aims to optimize the performance of MHPP in controlling the frequency and voltage stability when load changes occur by improving the ELC and VSI performance using Fuzzy-PI controller. ELC control the active power to maintain the frequency stability due to the load changes. Meanwhile, VSI control the reactive power to maintain the voltage stability in response to the changes in inductive loads. With a more stable frequency and voltage using the combination of ELC and VSI, the quality of the MHPP system output power will increase. The Proportional Integral (PI) control method is used to overcome errors and speed up the response time, while fuzzy logic is used to regulate the K_p and K_i parameters on the controller. The study results are expected to show that fuzzy-PI has better dynamic and static performance compared to the conventional PI controller and fuzzy logic.

2. Research Method

Figure 1 below depicts the schematic diagram of a Micro-Hydro Power Plant (MHPP) configuration, enhanced with an Electronic Load Controller (ELC) and Voltage Source Inverter (VSI) for precise frequency and voltage control. The central component, the generator, is responsible for generating electrical power in the form of both active power (Watt) and reactive power (Var). The generator operates under a constant mechanical power input and receives excitation voltage.

The primary powerhouse of this configuration is the generator, responsible for producing electrical power in both active (Watt) and reactive (Var) forms. The generator operates with a constant mechanical power input and is coupled with an excitation voltage injection mechanism.

The consumer load, comprising both active and reactive components, is subject to dynamic changes over time. To ensure an optimal system performance, the ELC and VSI control devices are strategically integrated in parallel with the consumer load. ELC plays a pivotal role by efficiently absorbing any excess active power. This strategic absorption ensures that the generator maintains a steady output of active power, even during periods of low demand. Notably, the ELC includes a resistive load known as the ballast load, designed to absorb active power and stabilize the system.

Conversely, VSI is responsible for precisely managing reactive power requirements of the system. The comprehensive configuration results in a highly responsive system are capable of swiftly adapting to fluctuations in consumer load. The objective is to consistently uphold the frequency and voltage levels within the acceptable limits, a crucial feature during periods of variable load conditions in the Micro-Hydro Power Plant system.

In essence, the sophisticated integration of the ELC and VSI components ensures robust control over active and reactive power, contributing to the overall stability and reliability of the MHPP system.

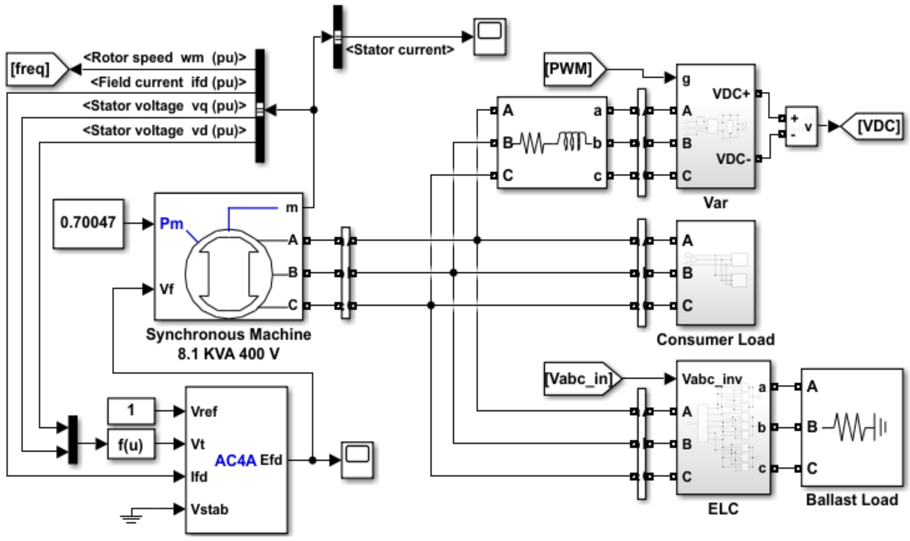

Figure 1. The Schematic of Micro-Hydro Power Plant (MHPP) with ELC and VSI Control

2.1 Voltage Control Design in VSI Circuit

In the VSI control, there is a regulation of the DC voltage. With Equation 1 and Equation 2, the DC voltage control value is generated by comparing the measured DC voltage with the DC voltage reference value. The output of the DC voltage control is in the form of the reference current value on the d-axis. This reference current value is then used to calculate the error value of the d-axis current. The resulting error is fed into the current controller to determine the input value required for the generator reference voltage.

In Equation 3 and Equation 4, the generator reference voltage signals the PWM generator to trigger the thyristors in the VSI circuit. The operation of the control system is synchronized with the phase-locked loop (PLL) in the Micro-Hydro Power Plant system.

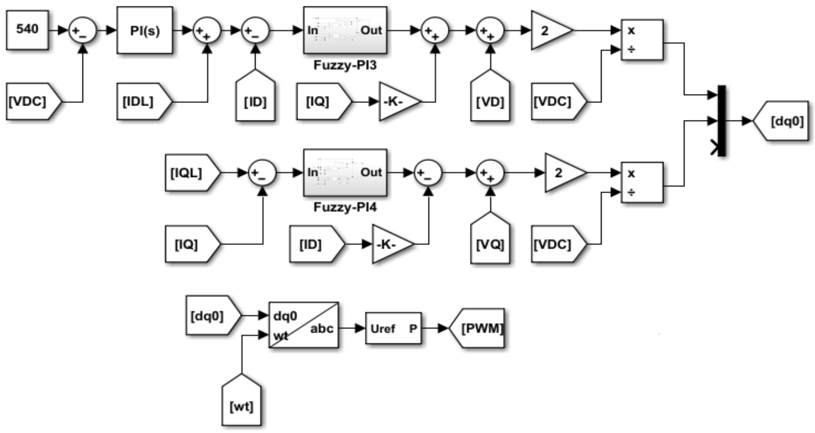

Figure 2. VSI Block Diagram System

DC Control:

$$I_{dref} = \left(V_{dcref} - V_{dc}\right) \times \left(K_p + \int K_i dt\right) \tag{1}$$

$$V_{dc} = \left(I_d - I_{dref}\right) \times \left(K_p + \int K_i \, dt\right) \tag{2}$$

Current control:

$$V_{d_{mes}} + I_d \times R - I_q \times L + \frac{dI_d}{dt} \times L = V_{d_{conv}} \tag{3}$$

$$V_{q\_mes} + I_d \times L - I_q \times R + \frac{dI_q}{dt} \times L = V_{q\_conv} \quad (4)$$

The Load-Side Converter Control:

After comparing with the reference values, the voltages on the d-axis and q-axis components can be adjusted using the voltage regulator. The Equations 5-13 show that the output voltage from the VSI depends on the modulation index and DC voltage.

$$V_{Line} = \frac{m}{2}\sqrt{\frac{3}{2}}V_{dc} \quad (5)$$

$$V_d = \left(V_{dref} - V_{dmes}\right) \times (K_p + \int K_i\,dt) \quad (6)$$

$$V_q = \left(V_{qref} - V_{qmes}\right) \times (K_p + \int K_i\,dt) \quad (7)$$

Inverter filter equation:

$$C\frac{d\underline{V}_{cf}}{dt} = \underline{I}_{inv} - \underline{I}_{load} \quad (8)$$

$$L\frac{d\underline{i}_{inv}}{dt} = \underline{V}_{inv} - V_{cf} \quad (9)$$

Equation for d-q components:

$$\underline{V}_{q(cf)} = \frac{1}{C}i_{q(inv)} - \omega V_{d(cf)} - \frac{1}{C}i_{q(load)} \quad (10)$$

$$\underline{V}_{d(cf)} = \frac{1}{C}i_{d(inv)} + \omega V_{q(cf)} - \frac{1}{C}i_{d(load)} \quad (11)$$

$$i_{q(inv)} = \frac{1}{L}V_{q(inv)} - \omega i_{d(inv)} - \frac{1}{L}V_{q(cf)} \quad (12)$$

$$i_{d(inv)} = \frac{1}{L}V_{d(inv)} + \omega i_{q(inv)} - \frac{1}{L}V_{d(cf)} \quad (13)$$

Where ω, L, C, $\underline{V}_{cf}$, $\underline{V}_{inv}$, $\underline{I}_{inv}$, and $\underline{I}_{load}$ refer to the angular frequency of the voltage, inductance, capacitance, capacitor voltage from the LC filter, inverter output voltage, inverter current, and load current, respectively. If V_dc and I_dc are the measured DC voltage and current, the power balance equation is obtained by considering the capacitor against the required load as depicted in Equation 14 [15]:

$$V_{dc}I_{dc} = \frac{3}{2}(V_{q(cf)}i_{q(load)} - V_{d(cf)}i_{d(load)}) \quad (14)$$

2.2 ELX frequency control design

The design of the ELC control used employs Fuzzy-PI control as the standard regulation. The ELC control modeling is illustrated in Figure 3.

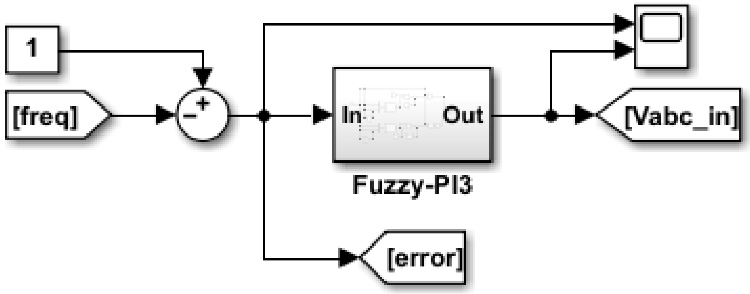

Figure 3. Block Diagram of ELC Control in Simulink

The ELC device connected to the generator involves modeling a synchronous generator with a power specification of 8.1 kVA, a frequency of 50 Hz, and a phase-to-phase voltage of 400 V. Both linear and non-linear three-phase loads are also considered in the simulation. Once connected to the generator and load, the ELC assumes the role of controlling load power to maintain a stable generator frequency. ELC control is implemented using an optimized control method that combines Fuzzy control and Proportional Integral (PI) control to achieve faster and more accurate control responses under load variations.

2.3 Fuzzy – PI Control Design

Fuzzy control involves two inputs: the error value and the first derivative of the error value. The results of these error and derivative error values are processed using Fuzzy rules to generate output parameter values, namely Kp and Ki [1]. The Kp and Ki values are then utilized to adjust the closed-loop response in the PI controller, with two outputs for each parameter of the PI controller. To determine these values, a Fuzzy Inference System is designed using the Fuzzy Toolbox in MATLAB, as illustrated in Figure 4.

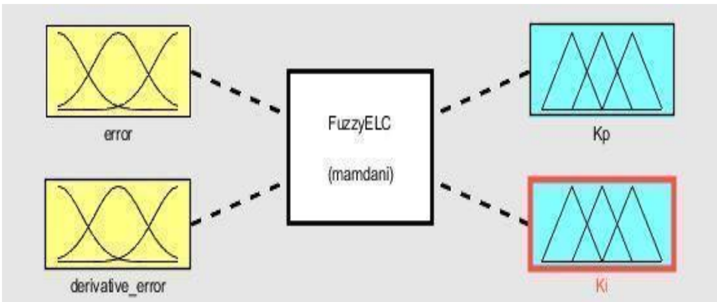

Figure 4. Designing the Relationship Between Fuzzy-PI Control Input and Output

In the design of the membership functions, the input consists of 5 linguistic variable levels in Fuzzy. The variables used for the input error and derivative error are NB: Negative Big, NS: Negative Small, Z: Zero, PS: Positive Small, and PB: Positive Big. The linguistic variables for the output are labeled as S: Small, MS: Medium Small, M: Medium, MB: Medium Big, and B: Big. Each output variable has values ranging from 0 to 1. The 25 Fuzzy rules base for the composition of the input and output is provided in Table 1.

Table 1. Rule Base Fuzzy Matrix Configuration

e/de	NB	NS	Z	PS	PB
NB	S	S	MS	MS	M
BS	S	MS	MS	M	MB
Z	MS	MS	M	MB	MB
PS	MS	M	MB	MB	B
PB	M	MB	MB	B	B

3. Results and Discussion

To assess the performance of fuzzy-PI control in the ELC and VSI circuitry, simulations were conducted using Simulink in Matlab. The Simulink model design is depicted in Figure 1. The performance analysis of the control system in the simulation adheres to the outlined scheme in Table 2.

In the initial condition, the generator supplies power to the consumer load equally and continuously until the 20th second. At the 20th second, the consumer load experienced a reduction in active power consumption by 700 Watts.

Subsequently, at the 35th second, there was a decrease in active power by 500 Watts in the consumer load, followed by an addition of 1000 Var of reactive power. The consumer load then underwent an increase in active power by 500 Watts and a reduction in reactive power by 1000 Var at the 50th second. Finally, at the 65th second, there was an additional 700 Watts of active power in the consumer load.

The performance of the ELC circuitry was evident during changes in frequency caused by alterations in active power in the consumer load. Meanwhile, the performance of the VSI circuitry was observable during voltage fluctuations, which occured when the consumer load experienced an increase in reactive power. Thus, both the ELC and VSI circuits were tested using the consumer load pattern changes as outlined in Table 2.

Table 2. Scheme of Consumer Load Variation

Time (second)	Active Power (Watt)	Reactive Power (Var)
20	-700	0
35	-500	+1000
50	+500	-1000
65	+700	0

The efficacy of fuzzy-PI control in the ELC and VSI circuitry became apparent when examining several key parameters, such as the total active power of the system, active power consumption by the load, active power absorbed by the ballast load, total reactive power of the system, frequency, and voltage. Figure 5 illustrates the dynamic changes in consumer load demands, involving both decreases and increases to the active load imposed on the generator at predefined time intervals. This nuanced response showcases the nuanced and adaptive nature of the fuzzy-PI control, demonstrating its effectiveness in maintaining system stability and meeting varying load requirements.

There was a reduction at the 20th and 35th second amounting to 700 watts and 500 watts respectively, resulting in excess power generated by the generator being redirected to the ballast load. The addition of active load to the consumer occurred at the 50th and 65th second, amounting to 500 watts and 700 watts respectively. Therefore, it is evident that the ELC effectively manages the active power on the ballast load to ensure the demand load is met.

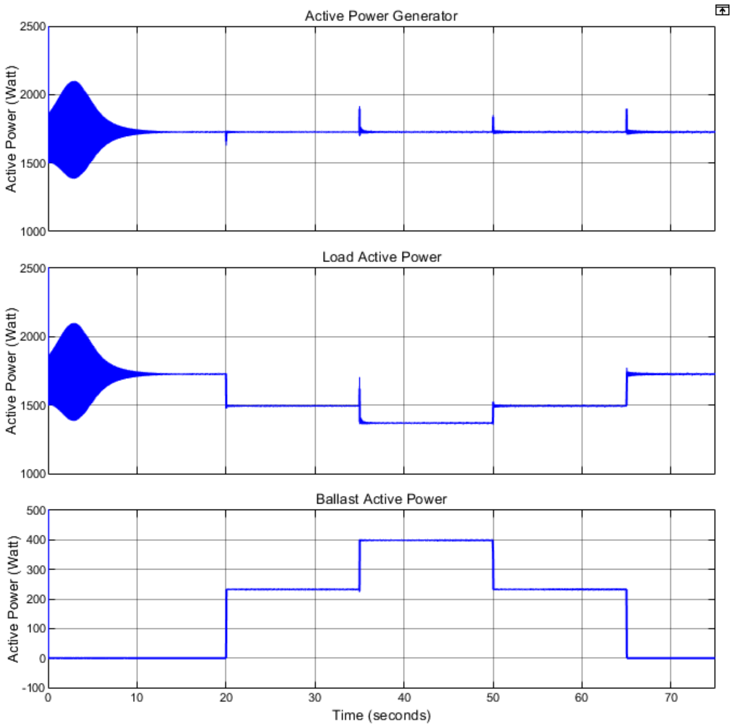

Figure 5. Comparison of Active Power: Generator, Consumer Load, and Ballast Load

In Figure 6, a discernible augmentation of reactive power in the consumer load was observed at the 35th second, registering a magnitude of 1000Var, followed by a subsequent decrement at the 50th second. Notably, during the infusion of additional reactive power, it became apparent that the Voltage Source Inverter (VSI) adeptly managed the generation of reactive power, ensuring the meticulous fulfillment of reactive power requisites within the consumer load.

This operational finesse contributed significantly to the reduction of voltage drop, underscoring the efficacy of the VSI in maintaining voltage stability.

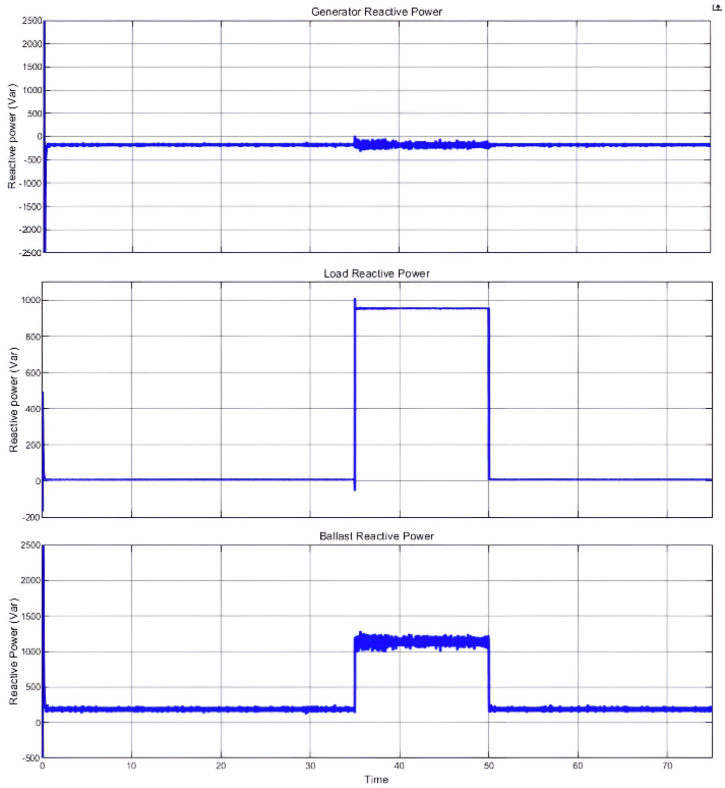

Figure 6. The Reactive Power Graph in the Presence of VSI Connection

In Figure 7, pertaining to load voltage, the graph reveals a stable voltage condition at 218 volts. However, at the 35th second, a voltage dip to 217 volts occurred due to the increase of reactive power to the load. A comparative analysis of the two controls in the figure suggests that the Fuzzy-PI control exhibits a tendency towards greater stability compared to the PI control.

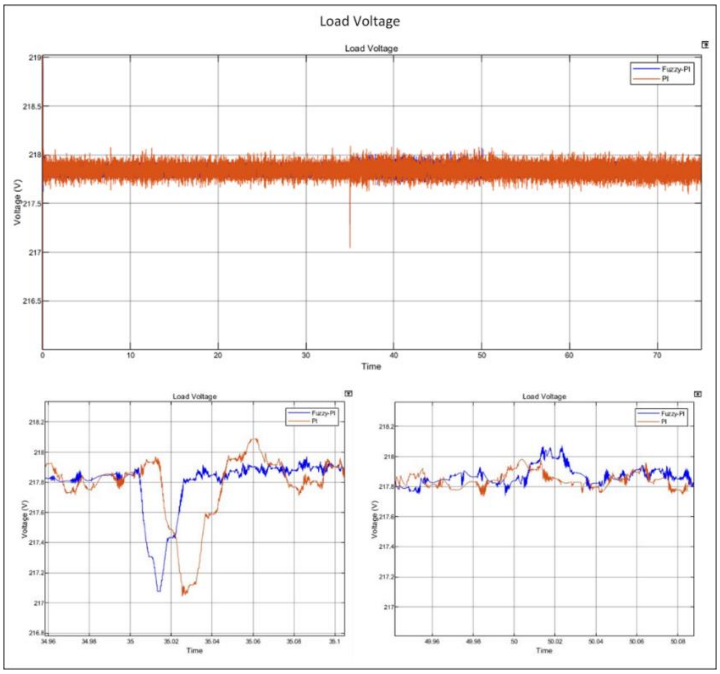

Figure 7. Voltage Graph with VSI

In Figure 8, pertaining to the load frequency, discernible variations were observed throughout each second, particularly in the initial seconds marked by the frequency surges. This dynamic frequency behavior is a consequence of load changes directed towards the ballast load. Notably, the graphical representation illustrates that the fuzzy-PI control attains the reference frequency more expeditiously compared to the PI control. This expeditious response can be attributed to the ability of fuzzy-PI control to yield a more pronounced reaction during the initial frequency shifts. Furthermore, the fuzzy-PI control demonstrates reduced oscillations in contrast to the PI control. In a broader context, the fuzzy-PI control emerges as an efficacious methodology for ELC systems, affording both prompt and stable responses.

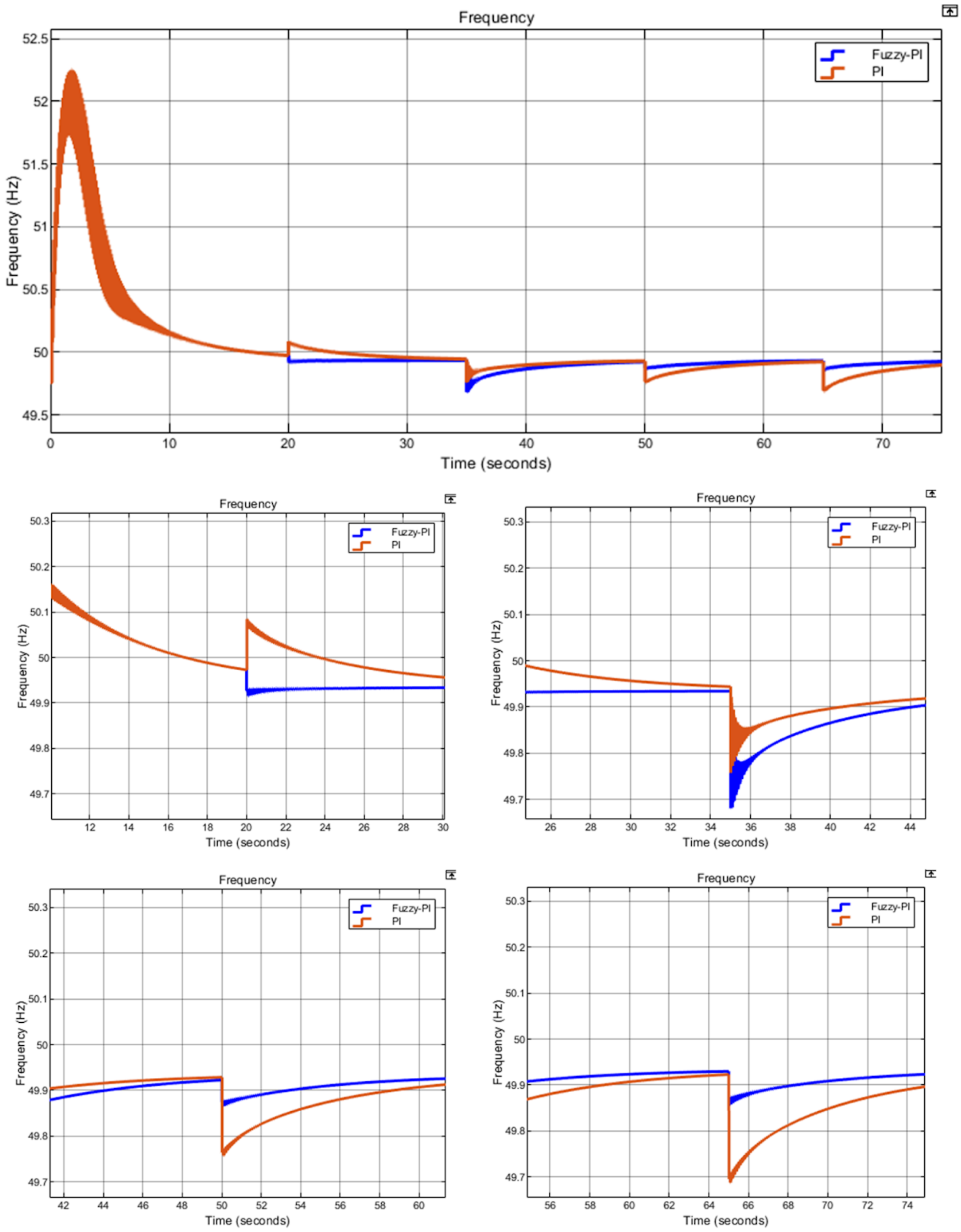

Figure 8. The Frequency Graph with ELC

4. Conclusion

The parallel integration of the ELC and VSI circuits with the generator and consumer load has demonstrated outstanding performance in regulating both frequency and voltage within the micro hydro power plant, particularly under varying consumer load conditions. The system's performance was evaluated across key parameters, including total active power, load active power, ballast load active power, total reactive power, frequency, and voltage. This study highlights the implementation of a fuzzy-PI controller within the ELC and VSI circuits. The ELC circuit plays a pivotal role in stabilizing the generator's active power, ensuring consistent frequency despite fluctuations in consumer load. Simultaneously, the VSI circuit effectively manages the generator's reactive power demand, thereby enhancing system voltage stability. The fuzzy-PI controller successfully mitigates oscillations in voltage and frequency, even during dynamic load changes. In conclusion, ELC and VSI using fuzzy-PI controller offers a reliable and robust solution for maintaining the stability and control of micro hydro power plants, meeting the intended operational objectives effectively.

Notation

The example of notation can be described with the following description:

V_{Line} : Phase voltage
V_{dc} : DC voltage
$\underline{I}_{load}$: Load current
$\overline{V}_{inv}$: Output voltage of VSI
$\underline{I}_{inv}$: Output current of VSI
K_p : *Gain* proportional
K_i : *Gain* integral
R : Resistance
L : Inductance
C : Capacitance
ω : Voltage angle frequency
m : Modulation index
I_{dref} : D-axis reference current
V_{dcref} : Reference DC voltage
$\underline{V}_{cf}$: Filter capacitance voltage
$\underline{V}_{d(cf)}$: Voltage capacitance of d-axis filter
$\underline{V}_{q(cf)}$: Voltage capacitance of q-axis filter
$V_{d(inv)}$: Output voltage of d-axis VSI
$V_{q(inv)}$: Output voltage of q-axis VSI
$V_{d_{mes}}$: Phase voltage of d-axis
V_{q_mes} : Phase voltage of q-axis
$V_{d_{conv}}$: D-axis voltage converter
V_{q_conv} : Q-axis voltage converter
$i_{q(inv)}$: Output current of q-axis VSI
$i_{d(inv)}$: Output current of d-axis VSI
I_d : D-axis current
I_q : Q-axis current
$i_{d(load)}$: D-axis load current
$i_{q(load)}$: Q-axis load current

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