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Power Quality Improvement in Micro Hydropower Plants through FPGA-Based Harmonic Elimination in Electronic Load Controller

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ABSTRACT

Micro hydropower plants (MHPP) have gained significant attention as renewable energy source due to their environmental friendliness and potential for local power generation. However, the presence of voltage and current harmonics due to the variations in the load of micro hydropower plants can deteriorate power quality and cause operational challenges. Traditionally, an electronic load controller (ELC) has been an essential part of the MHPP, whose main function is to keep the power consumption equal to the generated power in order to keep the voltage and frequency stable. In this paper, we propose an innovative approach to enhance power quality in MHPP through the implementation of an FPGA-based harmonic elimination technique in an ELC. The proposed system employs an FPGA-based ELC, which enables real-time monitoring and control of load characteristics. By employing an advanced harmonic elimination technique using a discrete-time PID controller inside the FPGA, the system effectively eliminates voltage and current harmonics, resulting in improved power quality. The FPGA-based implementation provides high-speed and accurate control, allowing for rapid response to dynamic load changes. Experimental results obtained from a prototype of the FPGA-based ELC design demonstrate the effectiveness of the proposed system in significantly reducing harmonics and enhancing power quality. Comparative analysis with traditional control techniques confirms the superiority of the FPGA-based approach in terms of harmonic elimination performance. The proposed system offers a cost-effective and reliable solution for enhancing power quality in micro hydropower plants, thereby facilitating their integration into the grid and promoting sustainable energy practices. The proposed design was

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first simulated in the MATLAB Simulink and then a complete hardware model was implemented using a Xilinx FPGA and tested on an MHPP site. It performed very well on the physical site.

Keywords: Micro hydropower plant, electronic load controller, PID controller, FPGA, turbine, synchronous machine, dummy loads, electronic switch, MATLAB, Simulink

1 Introduction

Presently, the entire world is facing an energy crisis due to a significant increase in population and industrialization [1][2]. Therefore, most countries are searching for new and sustainable energy sources. Micro hydropower plants have emerged as a promising renewable energy solution, providing sustainable electricity generation in remote areas with access to water resources [3][4]. In MHPP, the high water flow is utilized to rotate the shaft of the synchronous machine through a turbine and hence, electrical energy is generated. However, the proliferation of power electronics devices and nonlinear loads in modern power systems has led to the generation of voltage and current harmonics, which can severely impact the power quality of micro hydropower plants [5]. These harmonics not only introduce distortion in waveforms but also result in increased losses, reduced efficiency, and potential equipment failures. To address these power quality challenges, various techniques have been proposed, including the utilization of electronic load controllers. Electronic load controllers play a crucial role in maintaining stable and reliable operation by actively managing the load characteristics of the micro hydropower plant. By dynamically adjusting the load impedance, these controllers can regulate the flow of power and compensate for reactive power variations [6][7]. However, conventional electronic load controllers often struggle to effectively mitigate voltage and current harmonics due to limitations in their control algorithms and processing capabilities. In [8], an ELC was proposed using switching the dummy loads on the Zero crossings of the waveform, which effectively improved the power quality of the MHPP. However, there was a big room to further enhance the power quality by using a very fast controlling device like an FPGA, because in the hardware implementation of the previous design [8], an embedded controller running on only 16MHz was used, which is comparatively a very low speed.

Figure 1 shows the role of ELC in the power house. It can be seen, that the generated power is flowing toward the Consumer’s load and the ELC is continuously measuring the power consumed by the consumer’s load. After comparing the consumer’s load power with the generated power, the ELC will automatically turn ON and OFF the Ballast’s loads to equalize the generated power and consumed power [9][10].

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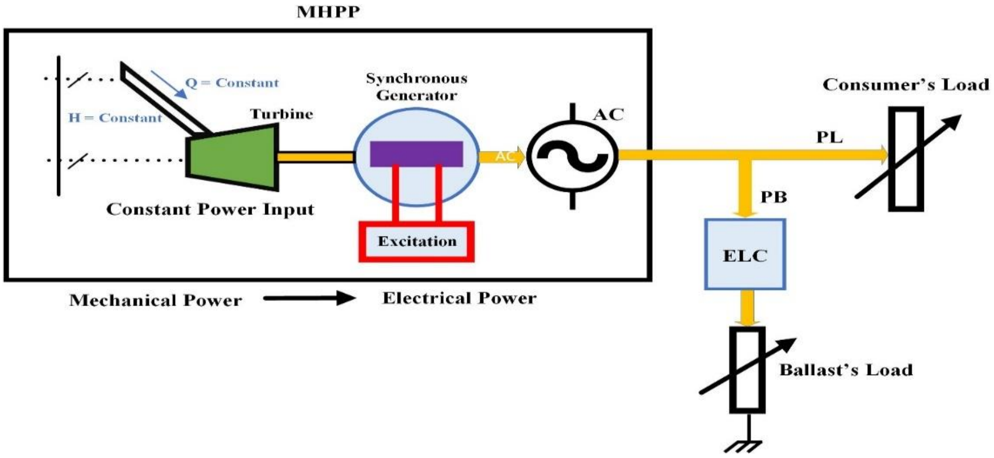

Figure 1 (The role of ELC in Power House)

The outcomes of this research are expected to contribute to the development of advanced power quality enhancement techniques for micro hydropower plants. The FPGA-based electronic load controller, with its ability to eliminate voltage and current harmonics, has the potential to enhance the overall performance, efficiency, and reliability of micro hydropower systems. By improving power quality, the proposed solution will facilitate the seamless integration of micro hydropower plants into the existing grid infrastructure, promoting the adoption of sustainable energy practices and supporting the electrification needs of remote communities.

2 Related Work

Different ELCs have been designed and employed on the physical sites of the MHPPs, from analog control to digital logic based control and further to the microcontroller based systems. This section discusses the literature survey of different techniques for controller design in MHPP. Singh et al well classified the types of mechanical and electrical control for the generator output voltage and frequency, as shown in Figure 3 [9]. Bengiamin & Chan described a control scheme using the variable structure systems concept to minimize mismatches in the generation as well as the consumption of power in electric power systems [11]. This scheme enhances the dynamic properties of the integral controller, originally based on a steady-state concept. Sheirah & Abd-EI-Fattah applied a self-tuning regulator using microprocessors to achieve this improvement in two-area interconnected power systems [12]. Another control scheme proposed by Lee et al. in 1991 utilized a comprehensive minimum variance plan for load-frequency and tie-line power control in a multi-area interconnected thermal power system [13]. This control algorithm computed area generator corrective control through a self-tuning algorithm, which minimized a generalized cost function considering system output and control effort weighting. Simulation studies revealed that these proposed control strategies outperformed conventional methods, particularly in dealing with system non-linearity [14]. In 1998, Lim et al. introduced a decentralized robust load-frequency controller for a multi-area power system. Their approach included a novel technique that excluded feedback from any immeasurable state. The simulation study considered system parameter uncertainties and generation rate constraints in a three-area power system. The design addressed incomplete state feedback and involved an analog robust load frequency controller [15]. Young-Hyun et al. suggested an extended integral control for load frequency control with generator rate constraints [16]. This was implemented in the speed-governor system, showing much better control performance compared to the conventional PI controller, eliminating overshoot.

Doan et al. proposed a new load frequency control method to decrease regulating capacity [17]. The approach was demonstrated using a three-area longitudinal system model, showing a reduction of 20% in the regulating capacity's decreased level set value for load based on a steady-state deviation of frequency and tie-line power flow deviation under step load disturbance.

Bevrani et al. developed an iterative linear matrix inequalities (ILMI) algorithm to compute the PI parameters of the controller for ELC synthesis in a three-control area power system with wide-ranging load changes [18]. The ILMI-based PI controller was shown to provide robust performance.

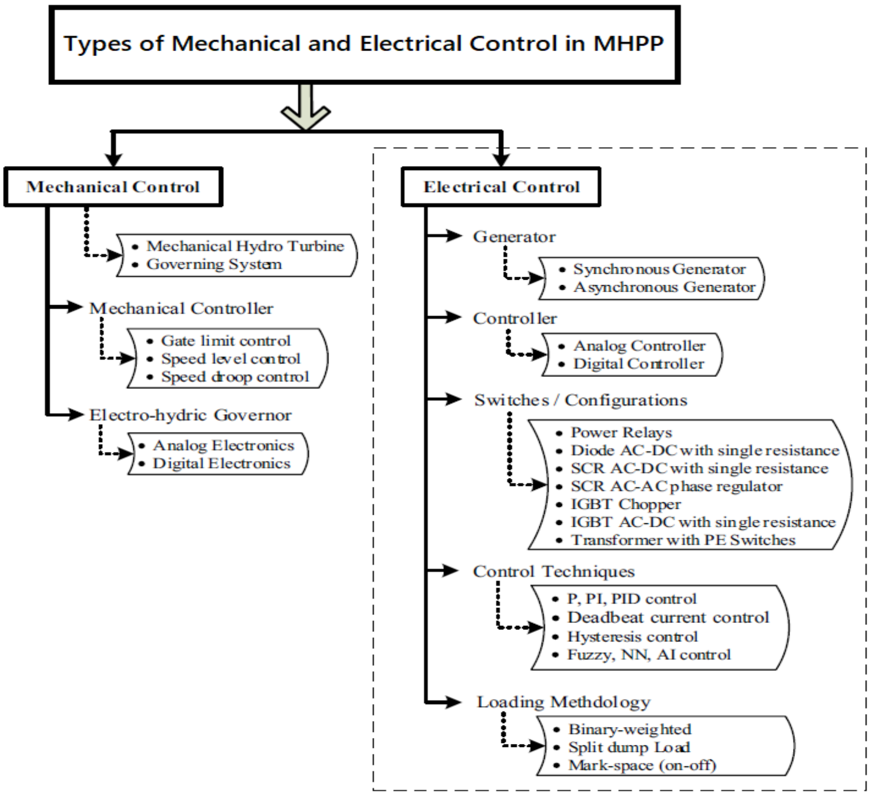

Figure 2 (Types of Mechanical and Electrical Controllers in MHPP) [9]

Singh et al. examined the advancements in ELC used in Small-Scale Micro-Hydro Systems (SMHS) and identified the limitations of existing technologies in this field [9]. A detailed classification of mechanical and electronic control in MHPP is presented by them, as shown in

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Figure 2. Following the review, they presented a new approach to improve the efficiency and lifespan of the generator by reducing the utilization of the dump load. The performance of the generator is experimentally evaluated using both conventional and proposed methodologies, while the estimated lifespan is determined by analyzing temperature profiles. Moreover, the proposed controller includes measures to protect the generator from sensor faults, thereby enhancing the overall system's reliability. Wen Tan proposed a tuning method based on a two-degree-of-freedom (TDF) internal model control (IMC) in a multi-area power system. The additional degree of freedom was used to cancel the effect of undesired poles of the disturbance, leading to improved disturbance attenuation performance in the closed-loop system. The study also implemented a decentralized PID tuning procedure [19].

In 2014, Swati Sondhi & Yogesh introduced a Fractional Order PID controller for ELC in a single-source multi-area system with different types of turbines [20]. The FOPID controller demonstrated better robustness towards ±50% parametric uncertainty and improved disturbance rejection capability compared to the integer-order PID controller. However, their work did not analyze the performance of the multi-source multi-area system. A. Ali et al suggested a new approach to turn ON and OFF the ballast's loads on the zero crossings. They proved with the help of simulation and physical model, that it resulted as the best method to minimize the voltage and frequency variations due to turning the nonlinear loads [8].

3 Proposed FPGA-Based ELC Model

A novel approach is presented to enhance power quality in micro hydropower plants by leveraging Field-Programmable Gate Array (FPGA) technology for harmonic elimination in electronic load control. FPGA is a programmable chip containing millions of logic gates and can be configured for any control-oriented function. FPGA-based systems offer several advantages, including high-speed processing, parallel computing capabilities, and programmability, making them ideal for real-time applications with demanding control requirements [21]. By implementing an advanced harmonic elimination technique by deploying a PID controller within the FPGA for the switching of dummy loads, the proposed system aims to eliminate voltage and current harmonics and achieve superior power quality. The key objective of this research is to design, develop, and evaluate an FPGA-based electronic load controller capable of effectively suppressing voltage and current harmonics in micro hydropower plants by switching the dummy loads on the Zero crossings of the waveform. The system will incorporate features such as harmonic detection, filtering, and compensation, allowing for accurate and real-time control of load characteristics. The FPGA-based implementation will enable rapid response to load variations and provide enhanced precision in harmonic elimination. The research methodology encompasses several stages, including system design, PID controller development using a hardware descriptive language (HDL), hardware implementation, and experimental validation. Extensive simulations and comparative analysis will be conducted to evaluate the performance of the FPGA-based system in harmonic elimination and power quality enhancement [22]. Furthermore, experimental tests will be carried out on a prototype micro hydropower plant to validate the practicality and effectiveness of the proposed solution.

Figure 2 presents the block diagram of the proposed FPGA-based ELC. The main principle of

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the ELC is to keep the power consumption equal to the generated power [23]. In this way, the unwanted harmonics will be automatically eliminated. Different parameters of the power coming from the generating side will be measured and fed through the XADCs to the PID part of the FPGA. The FPGA will compare these parameters with the reference values applied to it. If the generated power will be more than the current consumer's loads consumption, then it will automatically turn ON one or multiple dummy loads to make the difference between generated power and consumed power zero.

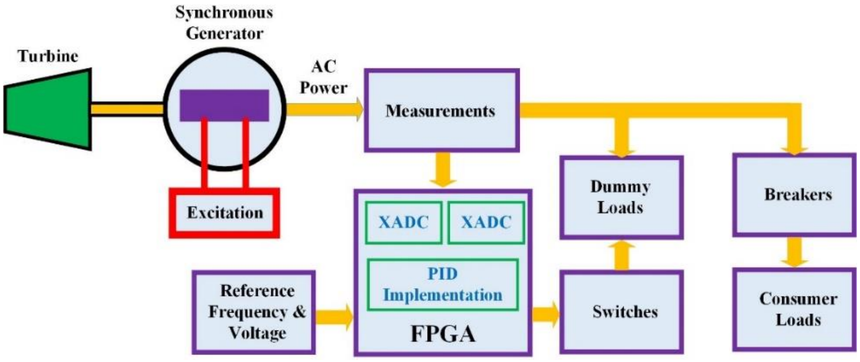

Figure 3(Block diagram of the proposed system)

Another prominent feature of the proposed design is, that, it will turn the loads ON and OFF on zero crossings of the AC waveform. In previous research, the same zero crossings technique was used, but that design was based on the low-speed microcontroller, which was taking much time in turning the loads. This design utilizes the power of an FPGA, so its response is very fast and turning the dummy loads in a small amount of time gives high-quality power to the consumer end.

4 Mathematical Model of the ELC

The mechanical power derived from a micro-hydro power turbine can be calculated by multiplying the effective head (H) and the flow rate of water (Q) [24]. However, due to practical limitations, the turbine is not 100% efficient, resulting in a decrease in turbine power (P_{mech}) based on an efficiency factor (η_{turb}).

$$P_{mech} = \eta_{turb} \rho g H Q \qquad (1)$$

The hydraulic power (P_{mech}), which drives the generator, is the input power of the turbine. A synchronous generator consists of a rotating electromagnet (rotor) and stationary conductors wound in coils (stator). When the rotor's field interacts with the conductors, alternating current (AC) is induced in the stator winding, generating electrical power. This electrical power (P_{elec}) is mathematically related to the mechanical power from the turbine, considering the efficiency of the generator (η_{gen}).

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$$P_{elec} = \eta_{gen} . P_{mech} \qquad (2)$$

The generated frequency (f) is dependent on the synchronous speed (N_s) and the number of poles
(P).

$$f = \frac{N_s P}{120} \qquad (3)$$

The ELC always keeps the sum of consumer load and dummy loads equal to the power generated.

$$P_{elec} = P_{cl} + P_{dl} \qquad (4)$$

5 Simulink Model of the Proposed ELC

The proposed ELC design was first simulated by the MATLAB/ Simulink environment and then implemented in hardware form by employing the Xilinx SOC. Figure 4 presents the Complete Simulink Model of the MHPP, Proposed ELC and dummy loads. This model of the proposed system includes a synchronous generator (SG) with a capacity of 200 kW.

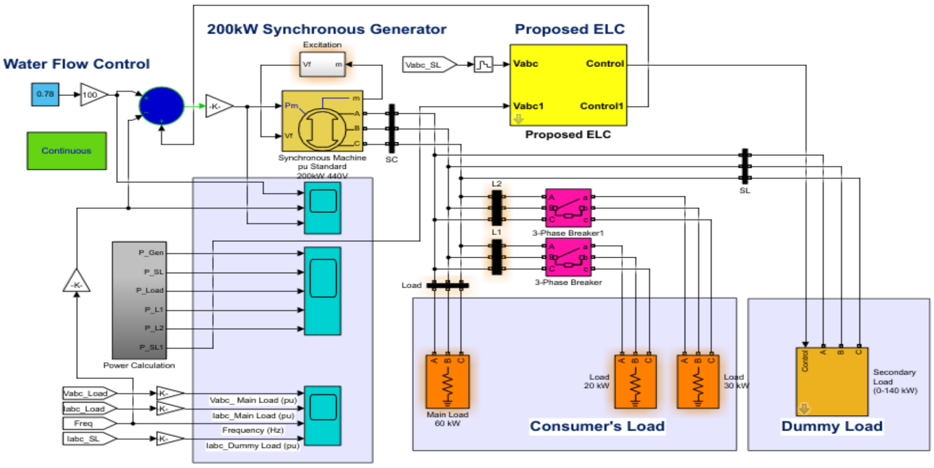

Figure 4 (Complete Simulink Model for the MHPP, Proposed ELC and dummy loads)

On the leftmost side, there is a water flow control and turbine model, which provides mechanical power to the Synchronous generator (SG). The SG is providing power to the consumer loads, which include one main load of 120KW and two sub-loads of 20KW and 30KW respectively. The sub-loads can be turned ON and OFF by the breakers at any time intervals. To evaluate the effectiveness of the FPGA-based ELC, the first sub-load of 20KW is turned ON at 2 second, while turned OFF at 3-second time intervals using the breaker-1. Similarly, the second sub-load of 30KW is turned ON at 5 seconds, while turned OFF at 6-second time intervals using the breaker-2. While the SG runs on a constant mechanical power input, the switching on and off of the domestic loads results in fluctuations in the frequency.

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These huge changes in the consumer loads will be the means of frequency variations and severe harmonics in the voltage and current of the MHPP and hence deteriorate the power quality. To counteract these frequency fluctuations, the Electronic Load Controller (ELC) detects the changes and activates or deactivates dummy loads connected to it. The generator's output frequency, voltage, consumer load currents, and ballast load currents are displayed in Scope 1. Scope 2 illustrates the generated power, the consumer's required power, and dummy load power. The generator outputs serve as input for the ELC, and the ELC, in turn, controls the ballast loads based on its output.

5.1 ELC Design

Figure 5 shows the proposed ELC Simulink model. The output of the generator is applied to the Phase Locked Loop (PLL), which measures the frequency of the generator output. This frequency signal and a reference frequency signal are then applied to the Add/ Subtract block, which calculates the difference between the both. This difference is then applied to the discrete type Proportional Integral Differentiator (PID) controller block, which will produce a control signal for the dummy loads. The control signals are produced in such a way, that, the dummy loads will be turned ON and OFF on the zero crossings of the generator’s voltage. The zero crossing detection is part of the sampling block. These control signals are then applied to the dummy loads through the Pulses decoder and sampling system, which will generate a bit pattern for turning ON and OFF the eight three-phase loads in such a way, that the generator frequency will be equalize to the reference frequency.

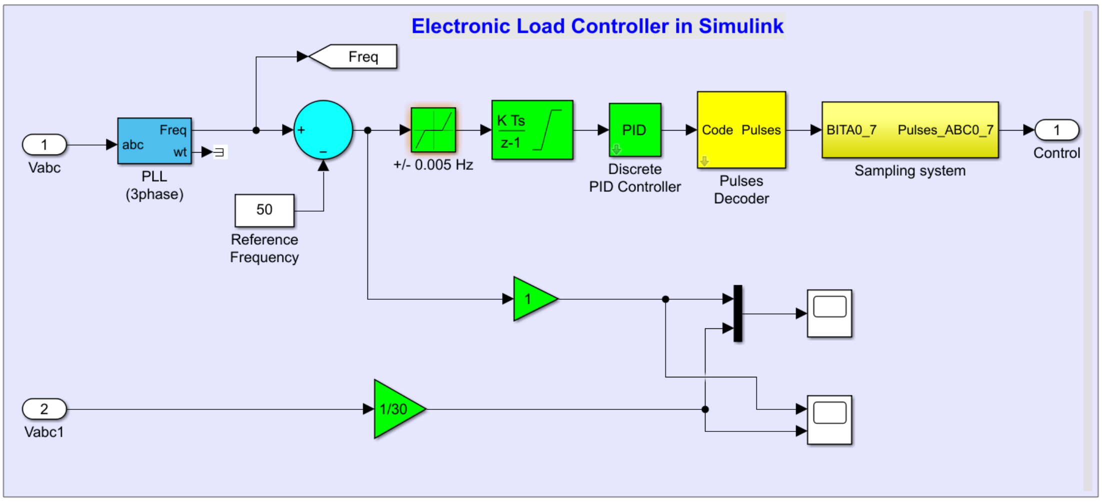

Figure 5 (Simulink Model of the Proposed ELC)

After a successful simulation of this model in Simulink, the model was then implemented on the Xilinx FPGA (ZYNQ 7000 SoC) [25]. The FPGA implementation is discussed in section 6, as this section covers the working of the Simulink model.

5.2 Discrete-time PID Controller

The main role in this design is the proportional–integral–derivative (PID) controller inside the

ELC block, which generates control signals for the dummy loads. The PID was invented in 1910 and after that, it has been widely used in different control-oriented applications. The reason for its popularity is its effectiveness, simplicity and robustness [26][27]. There are different configurations of the PID controller, but the mostly used design is given in Figure 6 [28]. In this ELC design the discrete PID controller is responsible for controlling the dummy loads to control the frequency of the generator. In the Simulink model the block of the PID controller has been used, while in hardware implementation of the ELC, the discrete-time PID controller has been deployed on the FPGA. Figure 5 shows the Block diagram of the discrete-time PID controller and its mathematical form is given in equation 5 [26].

$$\begin{aligned} u(k) &= k_I \frac{e_k}{1-z^{-1}} + k_P e_k + k_D(1-z^{-1})e_k \\ &= \begin{bmatrix} k_I & k_p & k_D \end{bmatrix} \begin{bmatrix} z_k \\ e_k \\ \Delta e_k \end{bmatrix} \end{aligned} \tag{5}$$

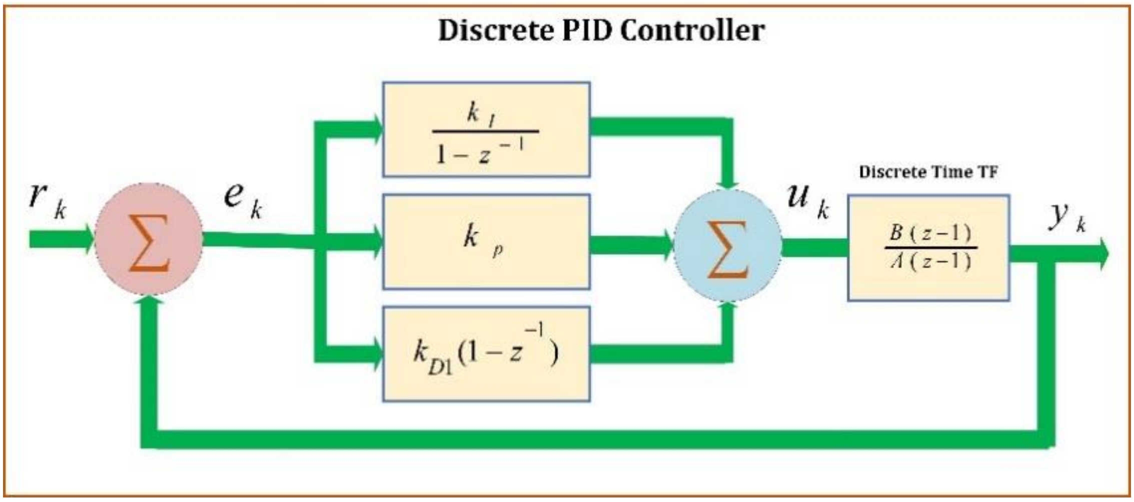

Figure 6 (Discrete PID Controller)

5.3 Zero Crossing detection and sampling system block

The sampling block shown in Figure 7 contains zero-crossing detectors, which detect the zero crossings of all three phases of the generator voltage. The control signals to the dummy loads are applied on the zero-crossings, as there will be a minimum disturbance in the current and voltage waveforms [8].

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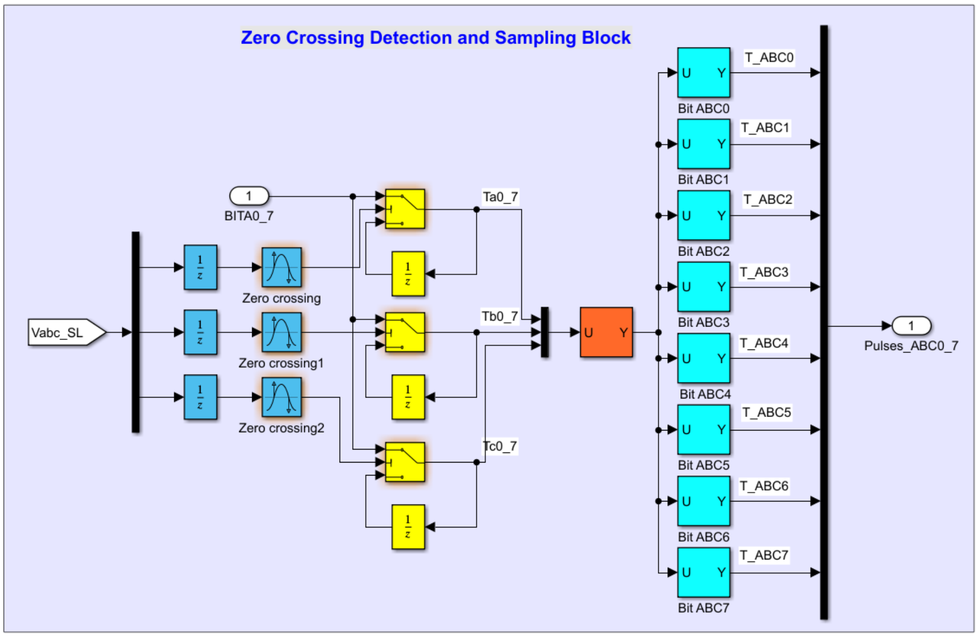

Figure 7 (Zero Crossing detection and sampling system block)

5.4 Design of Dummy Loads

The block of dummy loads contains the switches and three-phase resistive binary loads as shown in Figure 9.

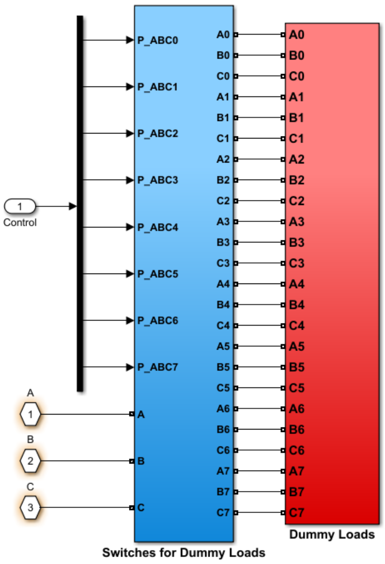

Figure 8 (Top view of the Switches and dummy loads block)

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Figure 10 shows the internal structure of the switches.

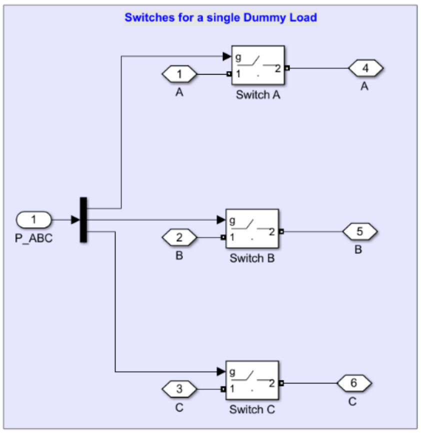

Figure 9 (Internal structure of switches block for a single binary dummy load)

Figure 11 shows the internal view of the three-phase binary loads.

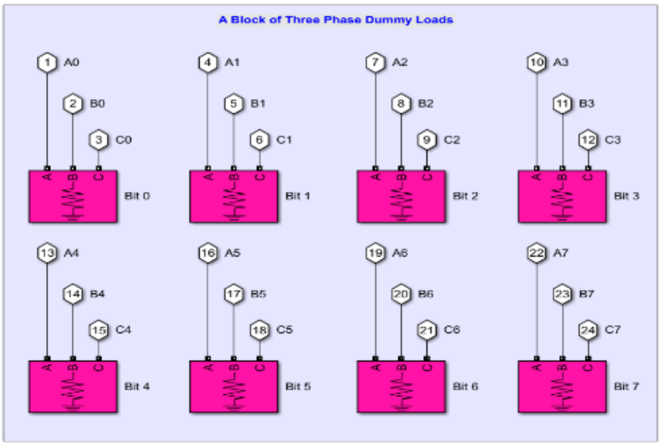

Figure 10 (Eight three-phase resisive dummy loads)

6 The design of FPGA-Based ELC

A novel idea of FPGA-based ELC is presented and implemented in this work. An FPGA can be configured as any high-speed electronic system, however, in this work, the important part of the ELC, a PID controller is implemented on the Xilinx FPGA. The results show, that due to the use of FPGA, the performance of the designed ELC is much better than the previous designs in terms of harmonic elimination and stable voltage and frequency output.

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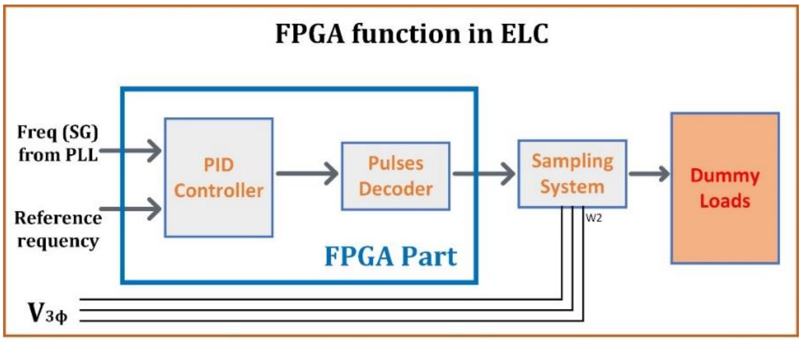

Figure 11 (The role of FPGA in ELC)

Figure 11 presents the function of FPGA in ELC. Two important blocks of the ELC model shown in Figure 5 have been implemented inside the FPGA. One part is the PID controller and the second block is the pulse decoder.

6.1 Schematic of the design on FPGA after Logic Synthesis and Implementation

Figure 12 shows the schematic diagram of the logic circuit implementation inside FPGA.

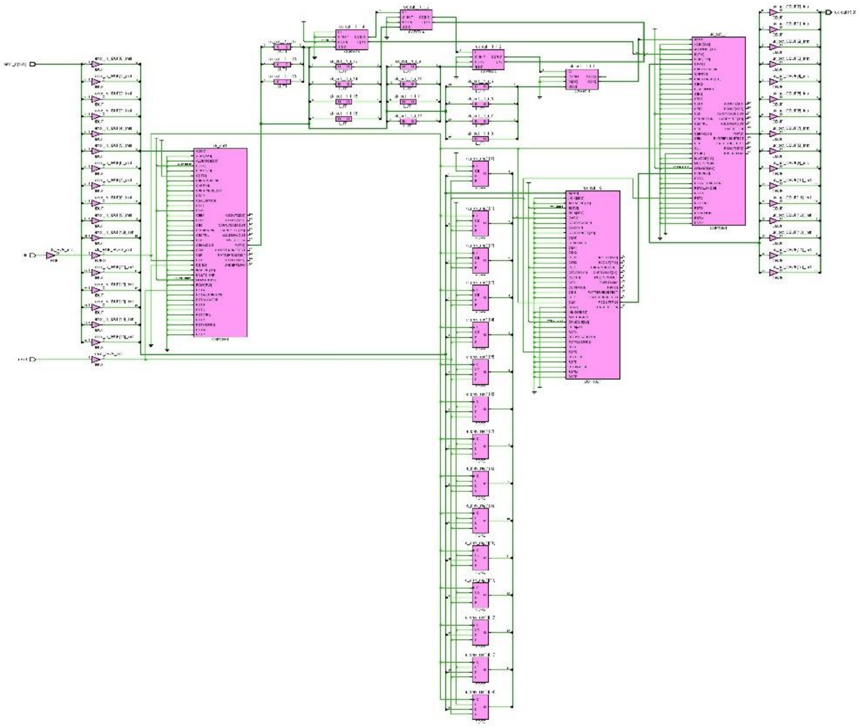

Figure 12 (Schemaic of the design on FPGA after Logic Synthesis and Implementation)

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The FPGA board used (ZedBoard ZYNQ 7000 SoC)

The proposed design requires a fast measurement of voltage and current signals coming from the generating side and then calculate the power consumption of the loads. For this purpose, a very fast device with both analog and digital signal processing is needed. After looking into all these requirements, the development board used in this research is the “ZedBoard Zynq Evaluation and Development Kit”, made by Digilent Inc [29]. The top view of this board is given in Figure 13. The device used on this development board is the Xilinx ZYNQ 7000 SoC, which contains a Programmable Logic (PL), a complete ARM Cortex A9 Processor, DSP blocks and dual channel 12 Bit ADC [25]. The XADC can be used to access 17 Multiplexed analog channels [25]. Many other peripherals are also there, so this board can be used for a wide area of diverse applications.

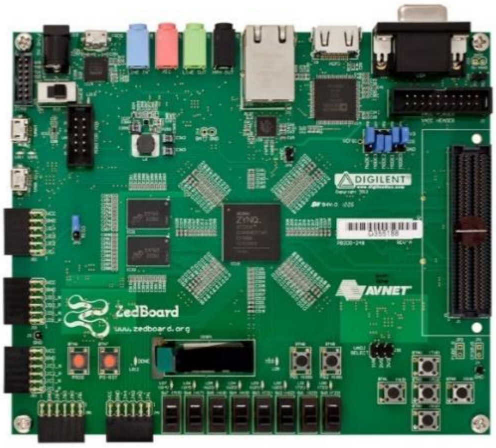

Figure 13 (The FPGA board, ZedBoard ZYNQ 7000 SoC)

7 Results and Discussion

This section discusses the results of this work. Figure 14 shows four different parameters of the system, the output voltage of the synchronous generator, the consumer load current, the generator frequency and the dummy load current. It is very much clear from the figure, that the three-phase output voltage is smooth and there are even no minor fluctuations. The second curve is showing the consumer load current. From 0 seconds to 2 seconds, the consumer load is low, but the dummy load current is high because the ELC has turned ON more dummy loads to match the consumed power equal to the generated power. At time 2 seconds, the consumer load has almost doubled and it can be seen, that the dummy loads have been changed immediately, but after a few milliseconds, the ELC has turned ON the required number of dummy loads. Since there is a huge change in the consumer current at 2 seconds, so there is a slight drift in the generator frequency, but within a few milliseconds, the frequency has been stabilized to the reference value, which is 50Hz in this case. So it proves, that the ELC is working fine.

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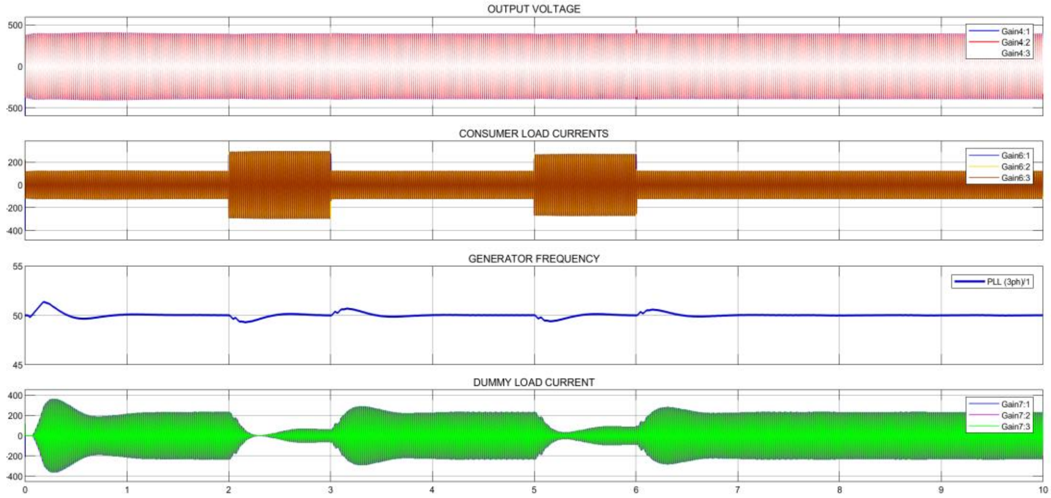

Figure 14 (The output voltage of SG, Consumer Load current, SG Frequency and Current of dummy load)

At time 3 seconds, the consumer load again came to a lower value and the ELC has again turned ON the dummy loads for a stable output voltage and frequency by equalizing the consumed power equal to the generated power. It is worth mentioning, that the ELC is doing all this process in a very short time as compared to the previous results. The same process has repeated on time 5 to 6 seconds and the same best response from the ELC.

Figure 15 and Figure 16 show a closer view of all the signals presented in Figure 15, which are the generator voltage, consumer load current, generator frequency and dummy load current. Figure 15 is concerned when the consumer load is changing from a lower value to a higher value, while Figure 15 represents the waveforms when the consumer load is changing from a higher value to a lower value. Due to the use of the proposed technique, the waveforms are very smooth, which proves, that the proposed method is an effective one.

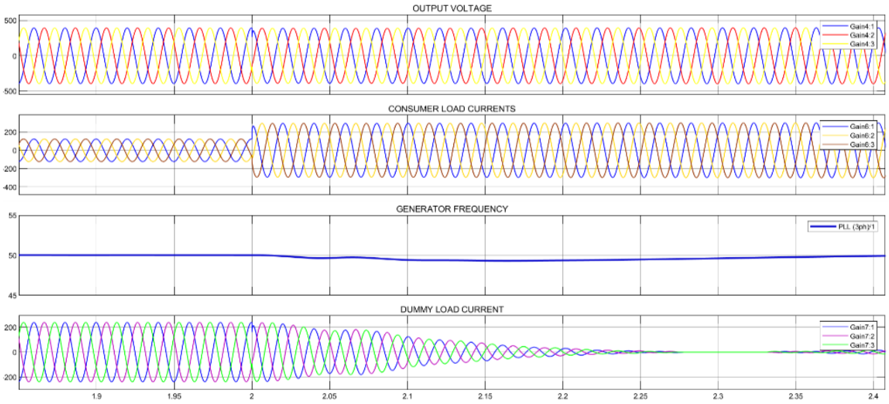

Figure 15 (Closer view of the waveform, when consumer load increased and dummy load decreased)

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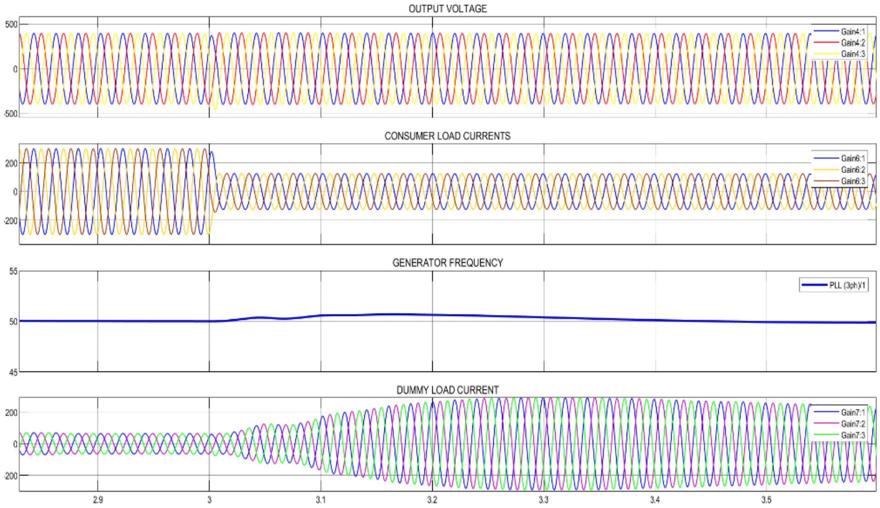

Figure 16 (Closer view of the waveform, when consumer load decreased and dummy load increased)

Here are the results of the different strategies adopted for turning ON and OFF the dummy loads in the ELC for MHPP. Traditionally, the loads were turned ON and OFF at random intervals, which was the means of creating the current and voltage harmonics in the output of SG. Such waveforms are shown in Figure 17. The total harmonic distortion (THD) of the SG output was 24.21%, shown in Figure 20.

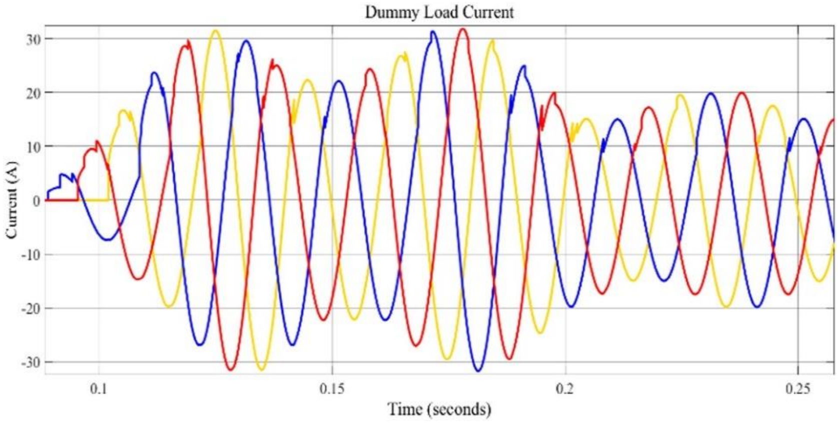

Figure 17 (Dummy Load Current with random-time switching)

In [8], an idea for this purpose was proposed, which was the switching of the loads on the zero crossings of the waveform. This was effective, as most of the harmonics vanished using this technique. The waveform is shown in Figure 18. The THD of the SG output was reduced to 3.59%, as shown in Figure 21.

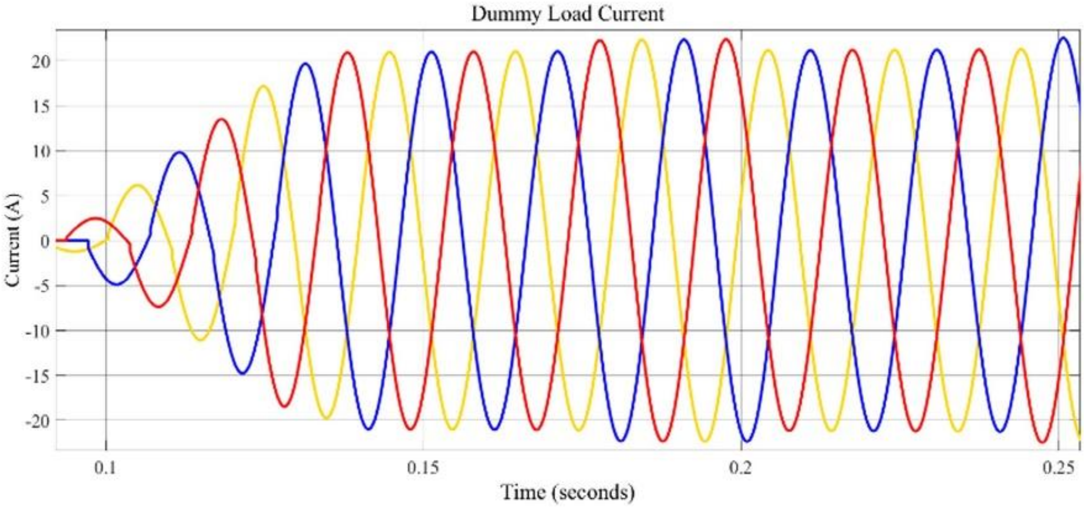

Figure 18 (Dummy Load Current with zero-crossings switching)

In the current proposed design, the same zero crossing switching along with FPGA-based fast signal processing and decision making is used. With this modification, the result is much better than the previous techniques. The THD by using this new strategy is 2.39% and it is a big achievement. The waveform of this new strategy is shown in Figure 18, which is comparatively much smoother than the previous waveforms.

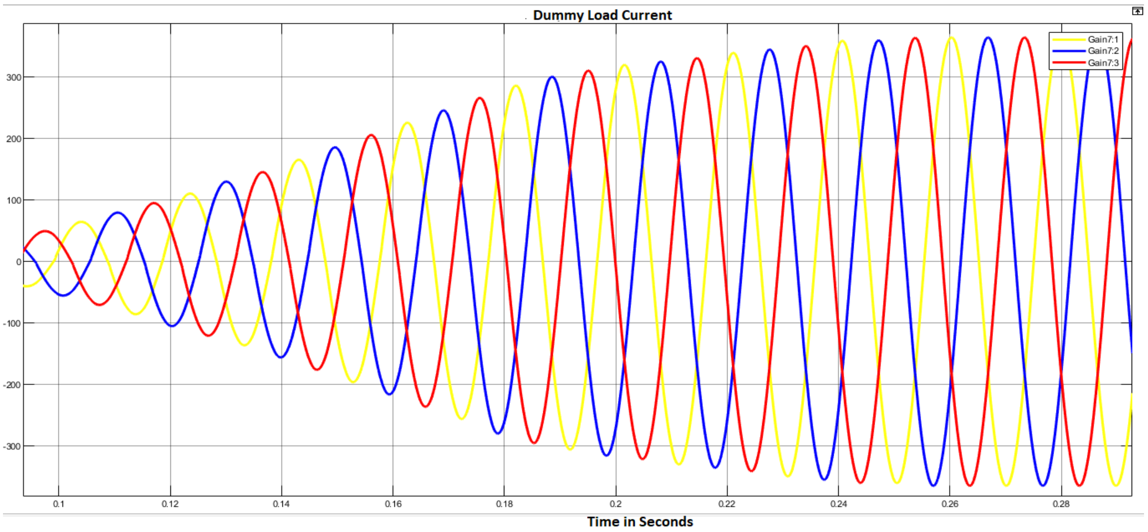

Figure 19 (Dummy Load Current of the proposed method with FPGA-Bsed PID and zero-crossings switching)

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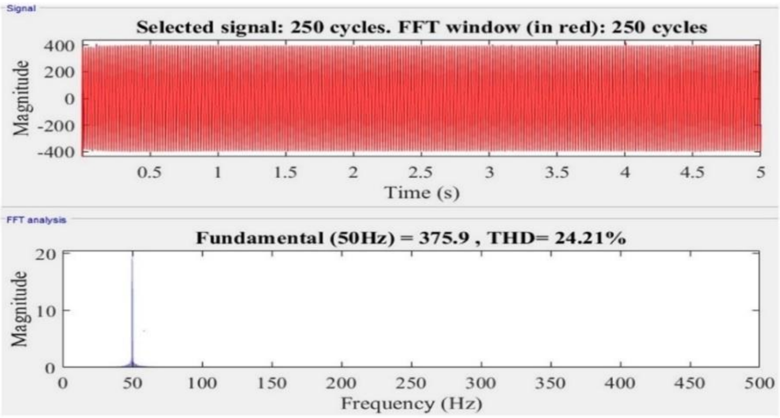

Figure 20 (FFT Analysis and THD graph by switching the loads at random-time)

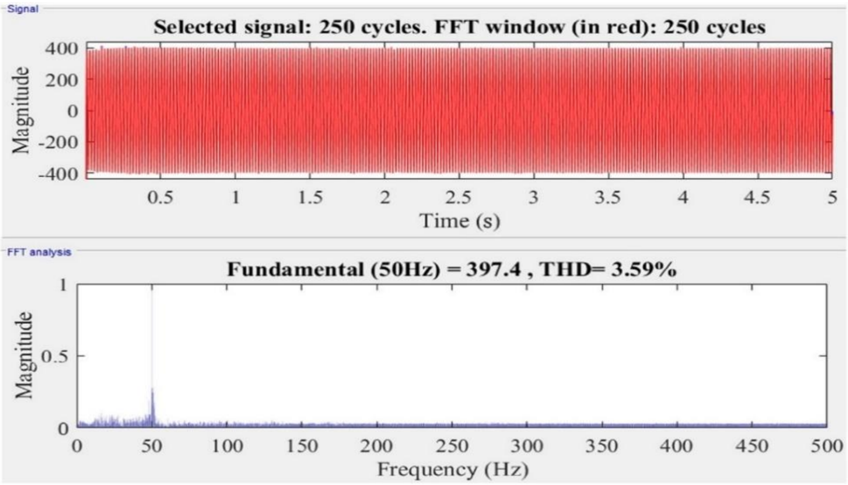

Figure 21 (FFT Analysis and THD graph with ELC with only zero crossing technique)

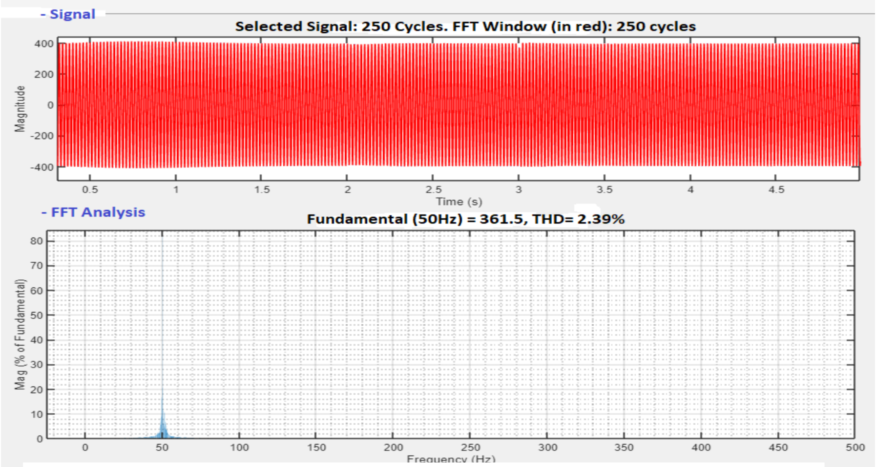

Figure 22 (FFT Analysis and THD graph using zero crossing method and FPGA)

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8 Hardware Implementation

Figure 23 presents the hardware implementation of the FPGA-based Electronic Load Controller. The proposed method was implemented on a Xilnix FPGA “ZINQ”. While a prototype of the current and voltage measuring circuits was also interfaced with the FPGA development board in the Laboratory.

Figure 23 (Experimental setup of the proposed system)

9 Conclusion

In this research, a new technique of using FPGA to perform fast data processing and making decisions was introduced and both simulation model and hardware implementation were carried out. The results showed much better performance in comparison with the previous techniques used for this purpose. The voltage and current waveforms were much smoother than the other designs due to the fast decision making capability of the FPGA. The total harmonic distortion (THD), which is a measure of checking the quality of the signals was reduced enough. So, it is concluded, that, this research activity will be a means of bringing quality in the output power of the Micro Hydropower Plants.

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