Development of an Intelligent Electronic Load Controller for Stand-Alone Micro-Hydropower Systems

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***Abstract*—People living in rural and remote areas of Sub-Saharan Africa generally lack access to electricity due to their geographical location and the costs associated with connecting these areas to the national electrical grid. A viable technology to supply electricity to some of these areas are stand-alone micro-hydropower systems which harnesses energy from flowing water. Self-excited induction generators (SEIGs) are commonly used for the generation of electricity in stand-alone micro-hydropower systems. The electricity supplied by a SEIG to the demand side i.e. the load needs to be maintained stable under various consumer load conditions. This is accomplished through the use of an electronic load controller (ELC). This paper presents the design and development of an intelligent ELC that is able to maintain stable voltage on the demand side of a 3-phase SEIG supplying varying single-phase consumer loads. The proposed intelligent ELC consists of an uncontrolled bridge rectifier, filtering capacitor, chopper switch, voltage sensor, optocoupler, Arduino microcontroller and a ballast load or storage, depending on site-specific requirements and economic viability. The fuzzy logic control method is implemented to maintain stable and reliable voltage. The ELC is designed and simulated under various consumer load conditions in Matlab/Simulink. Simulation results of the ELC model are verified experimentally in a laboratory setting. The proposed intelligent ELC will contribute towards providing reliable and cost-effective means of enhancing the proliferation of micro-hydropower particularly in rural and remote applications in Sub-Saharan Africa.**

***Index Terms*—Electronic Load Controller, Fuzzy Logic, Self-Excited Induction Generator, Stand-Alone Micro-Hydropower.**

I. Introduction

Electricity is an important factor in the economic development of a country. One of the major challenges in developing countries, especially Sub-Saharan Africa is the supply of reliable electricity to the people. According to the International Energy Agency an estimated 625 million people in Sub-Saharan Africa do not have access to electricity [1]. People living in rural and remote areas of Sub-Saharan Africa generally lack access to electricity due to their geographical location and the costs associated with connecting these areas to the national electrical grid. A viable technology to supply electricity to some of these areas is stand-alone micro-hydropower which harnesses energy from flowing water. Self-excited induction generators (SEIGs) are commonly used for the generation of electricity in stand-alone micro-hydropower systems due to its low cost, high reliability, less maintenance required, robust construction, no separate dc source required, brushless rotor operation and excellent protection against overloads and short circuits [2].

II. Electronic Load Controller

The electricity supplied by a SEIG to the demand side i.e. the load needs to be maintained stable under various consumer load conditions. This is accomplished through the use of an electronic load controller (ELC). An ELC diverts surplus power to a ballast load or storage in order to keep the power generated on the demand side by a SEIG stable. Various Electronic Load Controllers have been reported in literature [3] - [12]. The most commonly used methods to design an ELC are discussed briefly.

A. Binary-Weighted Load Regulation

In a binary-weighted load regulation the ballast load comprises of multiple resistive loads. Each resistive load is 2x the size of the previous resistive load. In order to keep the power output constant, a combination of resistive loads are either switched on or off (binary) according to changes in the consumer load. The binary-weighted load regulation is very complex and expensive as it requires a number of resistive loads, each with its own connections, wires and solid-state relays [13].

B. Phase Angle Regulation

A phase angle regulation comprises of a single resistive ballast load of magnitude equal to or slightly greater than the rated output value of the generator. Any change in the consumer load will result in the adjustment of the firing angle (α) of the switching device (thyristor or triac) and therefore current flowing through the ballast load is varied, thus maintaining a constant power output [13].

C. Mark-Space Ratio Regulation

The Mark-Space ratio regulation comprises of only a single ballast load. The ballast load is connected across an uncontrolled bridge rectifier that converts AC voltage produced by the generator to DC voltage. A transistor is used to switch the ballast load on and off with variable duty cycle. Any change in the consumer load will result in the varying of the on and off times (duty cycle) of the PWM output in order to achieve a constant power output. The duty cycle can be varied from 0% to 100% [14].

D. Controlled Bridge Rectifier

A controlled bridge rectifier regulation comprises of only a single ballast load. The ballast load is connected across a controlled bridge rectifier consisting of controllable thyristors that converts AC voltage produced by the generator to DC voltage. The thyristors are also used as control elements. Any change in the consumer load will result in the adjustment of the firing angle (α) of the thyristor and therefor current flowing through the ballast load is varied, thus maintaining a constant power output [8].

E. Uncontrolled Rectifier with a Chopper

An uncontrolled bridge rectifier with a chopper regulation comprises of only a single ballast load. The ballast load is connected across an uncontrolled bridge rectifier that converts AC voltage produced by the generator to DC voltage. An IGBT/MOSFET is used as a chopper (self-commutating switching device) to switch the ballast load on and off with variable duty cycle. Any change in the consumer load will result in the varying of the on and off times (duty cycle) of the PWM output in order to achieve a constant power output. The duty cycle can be varied from 0% to 100% [8]. This paper presents the design and development of an intelligent ELC that is able to maintain stable voltage on the demand side of a 3-phase SEIG supplying varying single-phase consumer loads.

III. System Description

A. Overview

A schematic diagram of the proposed intelligent ELC for stand-alone micro-hydropower systems is shown in Figure 1. The proposed system consist of the following:

- A prime mover: 3-phase 1.1 KW, star/delta, 400/230 V, 2.66/4.66 A, 50 Hz, 4-pole, 1420 rpm.
- A SEIG: 3-phase 550 W, star/delta, 400/230 V, 1.45/2.5 A, 50 Hz, 4-pole, 1395 rpm.
- 2 Excitation capacitors connected across the SEIG in the C-2C configuration: $C_1 = 16$ μF and $C_2 = 35$ μF.
- ELC consisting of an uncontrolled bridge rectifier, filtering capacitor, Insulated Gate Bipolar Transistor (IGBT), voltage sensor, optocoupler, Arduino Mega microcontroller and a ballast load or storage.
- Consumer load.

B. Operating Principle

The prime mover is used to drive the SEIG in order to generate electricity. An uncontrolled bridge rectifier is used to convert the SEIG AC voltage to DC voltage. A capacitor is used to filter out any unwanted ripples that the DC voltage of the rectifier contains in order to give out a smooth DC voltage. An IGBT is used as a chopper switch. A voltage sensor is used to sense the output voltage of the self-excited induction generator. An Arduino microcontroller is used to compare the sensed voltage with the reference voltage of 220 V. An error signal and change in error signal is generated after the comparison. These 2 signals are then multiplexed and fed to the fuzzy logic controller. The fuzzy logic control method is used to process these signals and generate an appropriate output signal. A PWM signal from the Arduino microcontroller is fed to the optocoupler and then to the IGBT. When the gate pulse to the IGBT is high, the current flows through the ballast load and consumes the difference in power, resulting in a stable voltage.

TABLE I: Results from parameter identification tests on experimental SEIG

Parameters	Values
Stator Resistance (R_s)	21 Ω
Rotor Resistance (R_r)	13.04 Ω
Stator Leakage Inductance (L_s)	0.03485 H
Rotor Leakage Inductance (L_r)	0.03485 H
Mutual Inductance (L_m)	0.4902 H

C. SEIG Parameters

The DC, no-load and blocked-rotor tests were performed in order to design the components of the ELC [8]. The results obtained from the tests are listed in Table I.

D. Design of Electronic Load Controller

The following calculations were performed in order to design the components of the ELC.

1) Power: The power produced by the generator is kept constant by increasing the ballast load power to compensate for any drop in the consumer power.

$$P_G = P_B + P_C \tag{1}$$

where

$P_G =$ Generated power,

$P_B =$ Ballast load power, and

$P_C =$ Consumer power.

2) Uncontrolled Rectifier and Chopper Switch Voltage Rating: The voltage rating of the uncontrolled bridge rectifier and chopper switch (IGBT) will be the same. The DC output voltage is calculated as:

$$V_{DC} = \frac{2\sqrt{2}V_L}{\pi} = 207.07\ V \tag{2}$$

where

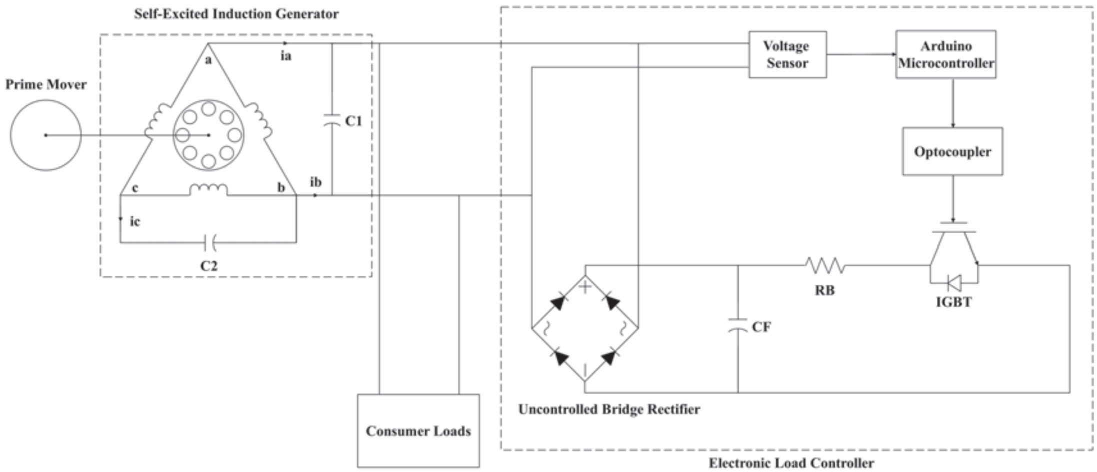

Figure 1: Overview of Micro-Hydropower System

V_{DC} = DC Output voltage, and

V_L = AC Input voltage of SEIG.

An overvoltage of 10% of the rated voltage is considered for the transient state and is calculated as:

$$V_{DC(10\%)} = \sqrt{2}\left(V_L + (0.1V_L)\right) = 367.80\ V \tag{3}$$

3) Uncontrolled Rectifier and Chopper Switch Current Rating: The current rating of the uncontrolled bridge rectifier and chopper switch (IGBT) is calculated as:

$$I_{AC} = \frac{P}{V_L} = 2.39\ A \tag{4}$$

where

I_{AC} = AC Current, and

P = Power rating of SEIG.

$$I_{Peak} = \frac{2\ I_{AC}}{0.9} = 5.31\ A \tag{5}$$

where

I_{Peak} = AC Peak current.

4) Ballast Load Resistance: The rating of the ballast load resistance is calculated as:

$$R_B = \frac{{V_{DC}}^2}{P} = 77.90\ \Omega \tag{6}$$

where

R_B = Ballast load resistance.

5) DC Filter Capacitance: The DC filter capacitance is calculated as:

$$C = \left(\frac{1}{4FR_B}\right)\left(1 + \frac{1}{\sqrt{2}R_F}\right) = 291.09\ \mu F \tag{7}$$

where

C = DC filter capacitance,

R_F = Ripple factor (20%),and

F = Frequency.

E. Fuzzy Logic Controller

A fuzzy logic system was designed using the MATLAB Fuzzy Logic Toolbox. A fuzzy logic system consist of the following four main parts used in the design procedure:

- Fuzzification
- Rule base
- Inference Engine
- Defuzzification

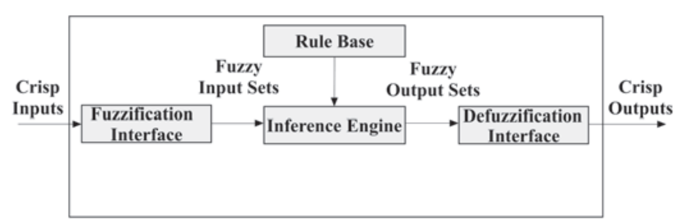

Figure 2: Fuzzy logic system

This fuzzy logic system consists of two inputs. The first input is error (e_k), which is the difference between the voltage set point (V_{SP}) and the actual voltage measured (V_{MS}), and the second input is change in error (Δe_k), which is the difference between the present voltage error (e_k) and the previous voltage error (e_{k-1}). The output (O) produces pulse width modulation (PWM) signals used for system control. The following equations describes the two inputs:

$$e_k = V_{SP} - V_{MS} \tag{8}$$

$$\Delta e_k = e_k - e_{k-1} \tag{9}$$

Both inputs consist of nine triangular membership functions as shown in Figure 3(a). The output consist of nine singleton membership functions as shown in Figure 3(b). A triangular membership function is a collection of 3 points forming a triangle using straight lines. For this design, triangular membership functions are used due to its simplicity and efficiency. For the two inputs and the one output these functions are: Negative big (NB), Negative medium (NM), Negative small (NS), Negative very small (NVS), Zero (Z), Positive very small (PVS), Positive small (PS), Positive medium (PM), Positive big (PB). The input range of the fuzzy logic system is between -20 and 20.

An example of these conditional statements used for control is if the error (e_k) is negative big (NB) and the change in error (Δe_k) is negative big (NB), then the controller should send a positive big (PB) output signal to bring the voltage of the system to the set point. If the error (e_k) is negative small (NS) and the change in error (Δe_k) is negative medium (NM), then the controller should send a positive medium (PM) output signal to bring the voltage of the system to the set point. If the error (e_k) is positive big (PB) and the change in error (Δe_k) is positive big (PB), then the controller should send a negative big (NB) output signal to bring the voltage of the system to the set point. The rule base design for the fuzzy logic system contains 81 fuzzy rules, represented in Figure 4.

The Takagi-Sugeno-Kang inference system develops a systematic approach in order to generate fuzzy rules from the input-output data sets. This inference system is used in the design due to its computational efficiency and its ability to work with optimization and adaptive control techniques. The defuzzification method used to obtain crisp output values from the inference engine is the weighted average method. This fuzzy logic system consist of one output. The output (O) produces pulse width modulation (PWM) signals used for system control. The output consist of nine singleton membership functions as shown in Figure 3(b). For the one output these membership functions are called the same as the two input membership functions. The output range of the fuzzy logic system is between 0 and 255. The control surface of the fuzzy logic system gives the two input membership functions and the output membership functions guided by the 81 fuzzy rules as shown in Figure 5.

IV. Simulation Results

The simulation of the SEIG and the intelligent ELC was carried out using Matlab/Simulink. The Simulink model was extensively simulated under various consumer load condition.

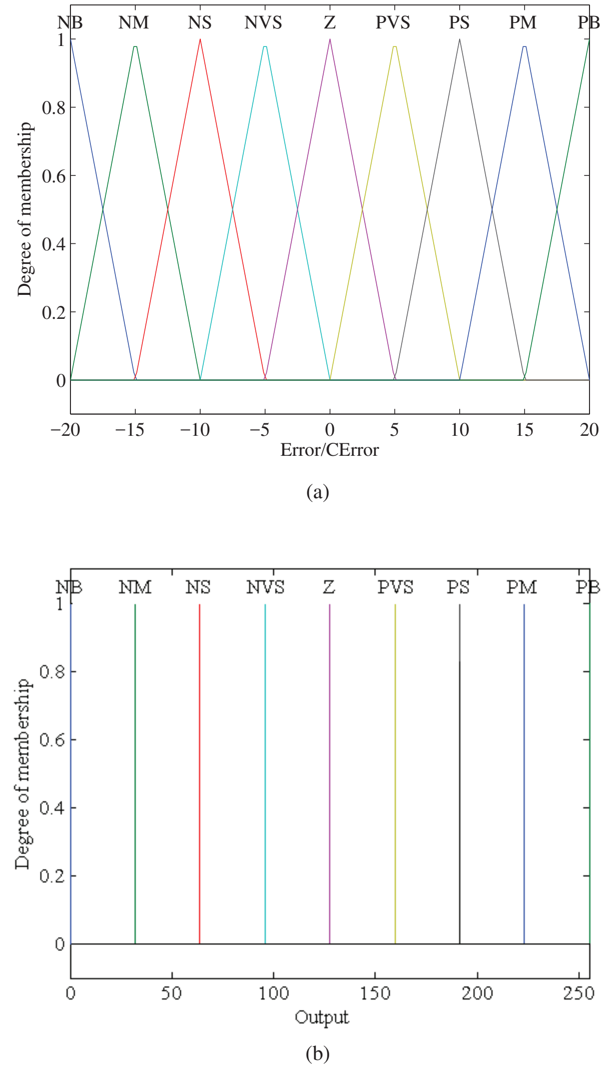

Figure 3: Memberships functions for (a) error and change in error, (b) output.

A. Simulation 1: Voltage Control Without ELC

Simulation 1 was done without an Electronic Load Controller as shown in Figure 6. The simulation was divided into three sections: Section A illustrates the generation of 230 V by the SEIG under no-load conditions. Section B illustrates the switching in of consumer loads. Section C illustrates an increase in the consumer load, causing the voltage to drop without recovering to the set point voltage of 220 V.

B. Simulation 2: Voltage Control With ELC

Simulation 2 was done with an Electronic Load Controller as shown in Figure 7. The simulation was divided into four sections: Section A illustrates the generation of 230 V by the SEIG under no-load conditions. Section B illustrates the switching in of consumer loads. Section C illustrates an increase in the consumer load, causing the voltage to drop.

Δe_k \ e_k	NB	NM	NS	NVS	Z	PVS	PS	PM	PB
NB	PB	PB	PB	PB	PB	PB	PB	PVS	Z
NM	PB	PB	PM	PM	PM	PS	PVS	Z	NVS
NS	PB	PM	PM	PM	PS	PVS	Z	NVS	NS
NVS	PB	PM	PM	PS	PVS	Z	NVS	NS	NB
Z	PB	PM	PS	PVS	Z	NVS	NS	NM	NB
PVS	PB	PS	PVS	Z	NVS	NS	NM	NM	NB
PS	PS	PVS	Z	NVS	NS	NM	NM	NM	NB
PM	PVS	Z	NVS	NS	NM	NM	NB	NB	NB
PB	Z	NVS	NS	NB	NB	NB	NB	NB	NB

Figure 4: Rule base design

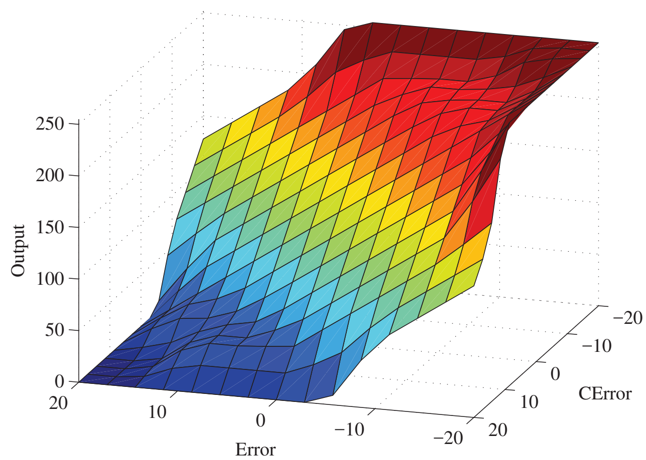

Figure 5: Control surface of fuzzy logic system

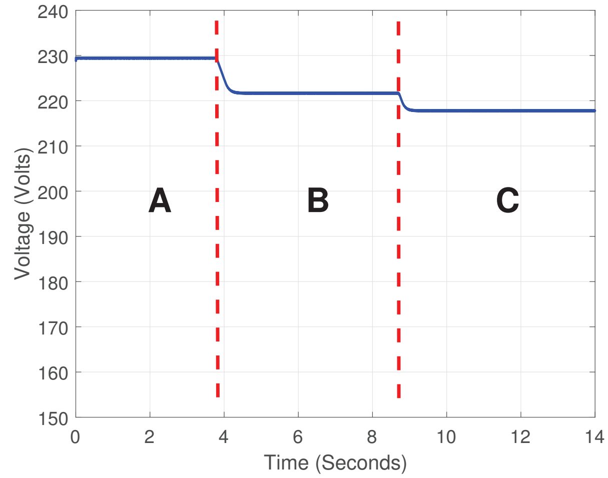

Figure 6: Voltage control without ELC

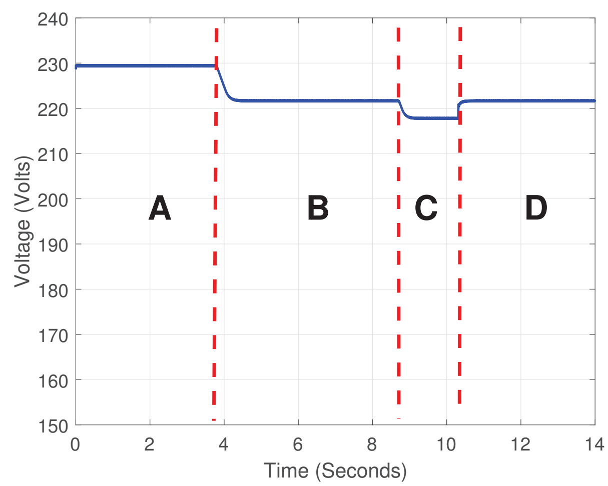

Figure 7: Voltage control with ELC

Section D illustrates the recovering of the voltage to 220 V by the ELC.

V. Experimental Results

Laboratory experiments were carried out on the proposed system under various load conditions to validate the operation and performance of the ELC (shown in figure 8). The prime mover is used to drive the SEIG in order to generate electricity. To generate the required voltage, 2 excitation capacitors are connected across the SEIG in the C-2C configuration. Resistive loads are used for both the consumer load and the ballast load. In the experiments carried out the consumer load was varied to demonstrate the response and control performance of the ELC.

A. Experiment 1: Voltage Control Without ELC

Experiment 1 was done without an Electronic Load Controller as shown in Figure 9. The experiment was divided into three sections: Section A illustrates the generation of 230 V by the SEIG under no-load conditions. Section B illustrates the switching in of consumer loads. Section C illustrates an increase in the consumer load, causing the voltage to drop without recovering to the set point voltage of 220 V.

B. Experiment 2: Voltage Control With ELC

Experiment 2 was done with an Electronic Load Controller as shown in Figure 10. The experiment was divided into four sections: Section A illustrates the generation of 230 V by the SEIG under no-load conditions. Section B illustrates the switching in of consumer loads. Section C illustrates an increase in the consumer load, causing the voltage to drop. Section D illustrates the recovering of the voltage to 220 V by the ELC.

VI. Future Work

The next step of this research will be to implement elements to enhance the system. A current sensor will be used

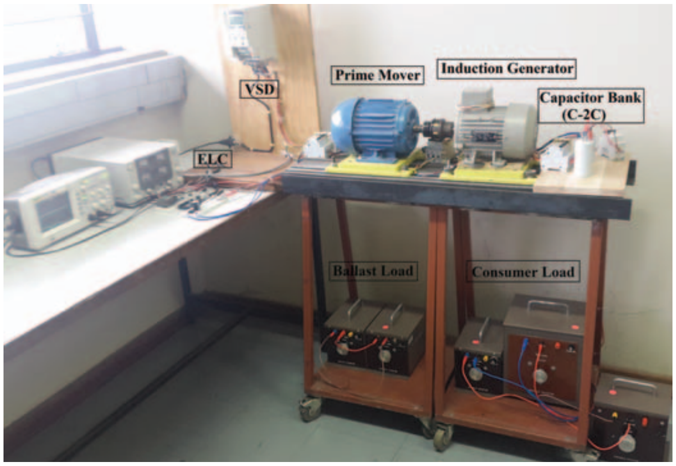

Figure 8: Experimental Setup

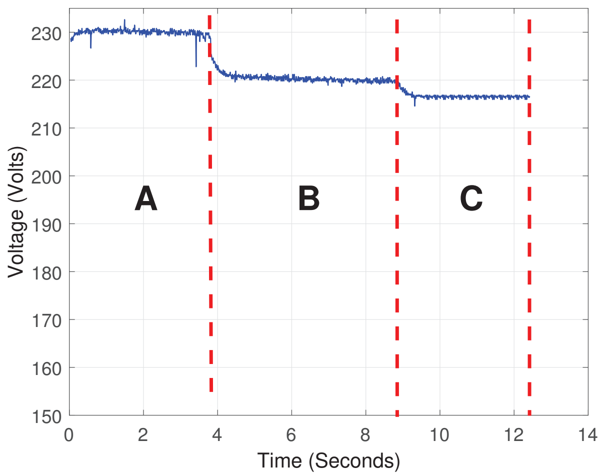

Figure 9: Experimental voltage control without ELC

to monitor the load current. Current measurement can be combined with the voltage sensor values to determine the power of the system and afford better control of the energy flow to and from the ballast. Different ballast loads such as battery banks will also be investigated. This will be used to supply electricity when the demand increases beyond what the micro-hydropower system is generating. Additionally, the testing of the Fuzzy-logic ELC under varying supply together with varying load conditions will be carried out.

VII. Conclusion

An intelligent ELC has been designed, tested and developed that is able to maintain stable voltage to the demand side of a 3-phase SEIG supplying varying single-phase consumer loads. The proposed intelligent ELC will contribute towards providing reliable and cost-effective means of enhancing the proliferation of micro-hydropower particularly in rural and remote applications in Sub-Saharan Africa.

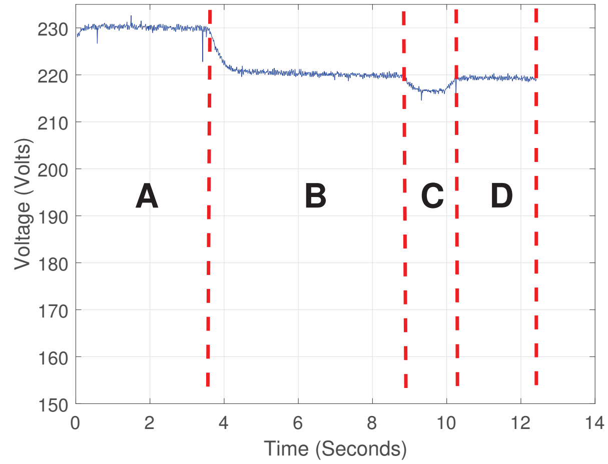

Figure 10: Experimental voltage control with ELC

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