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Analysis of Electronic Load Controller with Bidirectional Converter in Self-Excited Induction Generator

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A B S T R A C T

Induction generators are widely used in small-scale power plants driven by renewable energy, such as wind, mini/micro-hydro, tidal wave, biomass, biogas, etc. In applying this generator to a micro-hydropower plant, it is usually equipped with an ELC (Electronic Load Controller), which regulates the frequency to remain constant at a safe tolerance limit (49.8 – 50.2 Hz). However, this system is still not optimal because the ELC dumps its excess power into the dummy load. This paper proposes an ELC system that can adjust the frequency to remain constant without wasting excess power from the generator. This system uses the working principle of a bidirectional converter, which can regulate the flow of power from the generator and dummy load in two directions. In the proposed system, the dummy load uses a battery to store excess electrical energy and be utilized and reused when needed. Performance analysis of the proposed system uses simulation with MATLAB Simulink software. The induction generator used has a voltage specification of 380 Y, 50 Hz, 1420 rpm, 3.5 A, and 1.5 kW. The analysis results show that the developed ELC design can adjust the frequency in the value range of 49.98-50.01 Hz during load changes with a range of 955 Watt to 1.045 Watt, with the response time reaching its steady-state value of 0.1-0.4 seconds.

INTRODUCTION

Induction generators are widely used in small-scale power plants driven by renewable energy, such as wind, mini/micro-hydro, tidal wave, biomass, biogas, etc.[1-3]. This generator has been chosen because it has many advantages, such as easy maintenance, low price, and strong construction [4-5]. In applying induction generators to micro-hydropower plants, induction generators are usually equipped with an ELC (Electronic Load Controller) to overcome this generator's poor voltage and frequency regulation when it is loaded [4]. ELC is useful for keeping the frequency and voltage on the generator stable when there is a change in the load. One type of ELC that is widely known is built from an uncontrolled rectifier, DC chopper, dummy load, and DC link capacitor is the type of ELC [6-8]. The use of ELC is to balance the power between the generator output, the power on the consumer load, and the power on the dummy load. It is done by dumping excess power into the dummy load. The amount of power discharged to the dummy load is regulated using a DC chopper. However, this condition is not optimal because excess power is wasted. In order to solve the power dissipation problem in [9], an ELC system with a dummy load using a battery has been developed, but this is still not optimal. If the battery is full, the battery must be replaced immediately to make ELC work. To make the ELC with the battery to be used optimally, a bidirectional converter is needed to flow power in two directions between the battery and the generator line to the main load.

In the field of reactive power compensation technology, Static Synchronous Compensator (STATCOM) has been developed to regulate reactive power flow between the network and the capacitor/battery [10-12]. Likewise, in energy storage technology, STATCOM is also used to regulate active power flow between the network and electrical energy storage components [13-14]. For both these applications, STATCOM acts as an AC-DC bidirectional converter. In this study, we developed a concept of STATCOM technology as a bidirectional converter that can optimize the role of ELC in induction generators.

To optimize the function of ELC in induction generator, this paper proposes a system that can regulate the frequency of the generator to remain stable without having to waste excessive power. The excess power can later be stored and reused by the main load. The dummy load will later be replaced with a battery that can store excess electrical energy and be utilized and reused when needed. In regulating the flow of power from the generator, SATCOM is used as an AC-DC bidirectional converter, which

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can work to regulate the flow of power between the generator and the dummy load in two directions. The analysis of the proposed system is carried out by simulating the system design using MATLAB Simulink software. The study results can be used as recommendations and considerations in implementing the use of an AC-DC bidirectional converter on the ELC in the Self-Excited Induction Generator (SEIG) controlling.

METHOD

Unlike the synchronous generator, generating the voltage of SEIG does not require a DC source because it utilizes reactive power to generate its magnetic field so that it is easier to operate. However, this generator has poor regulation [15-16]. The generator voltage and frequency will change significantly when it is loaded. A system has been developed that can keep the voltage and frequency regulation of the generator stable when it is loaded. This system works by balancing the active power output of the generator with the active power consumed by the load or better known as ELC system [17]. The ELC system functions to improve voltage and frequency regulation for the better by dumping excess power into the dummy load. The ELC is installed in parallel to the load and the SEIG. Figure 1 shows the concept of regulation by ELC through active power balance. Voltage and frequency regulation in SEIG can be improved for the better by maintaining the active power balance based on the following equation:

$$P_{out} = P_L + P_C \tag{1}$$

where,

P_{out} = output power of generator

P_L = load power

P_C = absorbed power by dummy load

Here, the load power (P_L) varies according to the consumer's needs. The power absorbed by the dummy load (P_C) refers to the magnitude of the load power. It made the sum of the power of both (P_L+P_C) is equal to the generator's output power (P_{out}).

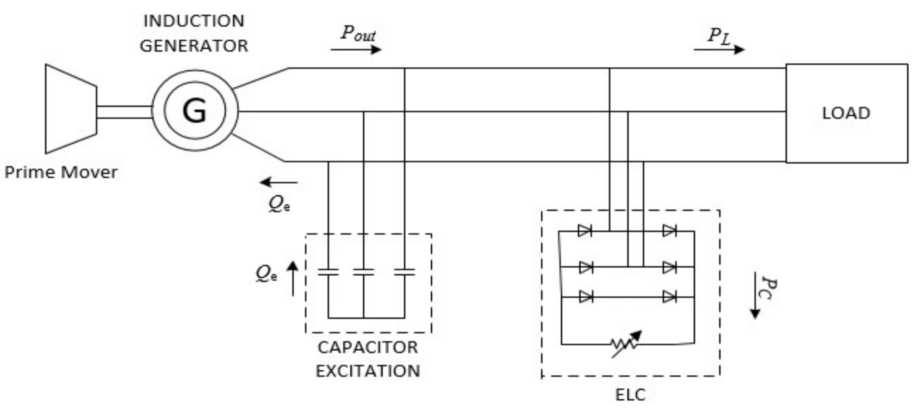

Figure 1. The power balance concept on SEIG with ELC

ELC with DC Chopper and Resistive Dummy Load

ELC with DC Chopper and Resistive Dummy load has been developed by Bhim Singh et. al. for the first time [6-7]. This ELC is constructed from an uncontrolled bridge rectifier, DC filter, DC chopper, and dummy load in the form of resistive load, as shown by Figure 2. The DC filter will flatten the dc voltage generated by the Uncontrolled Three-Phase Rectifier. DC chopper serves to regulate the amount of power that flows to the dummy load. DC Chopper uses the PWM (Pulse Wide Modulation) method to regulate the amount of power that will be thrown away to the dummy load by controlling the amount of duty cycle on the signal inputted to the DC chopper.

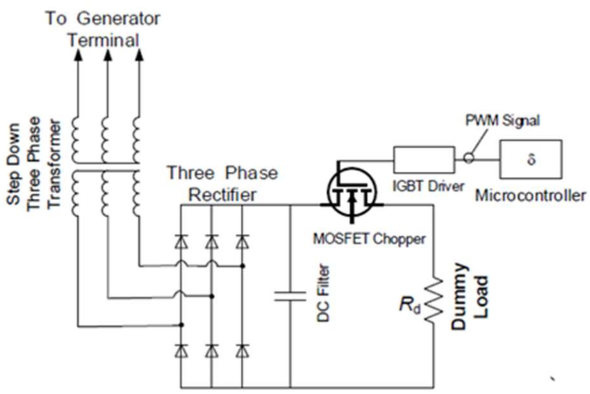

Figure 2. The configuration of ELC with DC chopper and resistive dummy load

ELC with DC Chopper and Battery Dummy Load

The ELC system discussed in sub-chapter 2.1 has drawbacks in optimizing utilization power generated by SEIG because excess power is wasted. The wasted power should be reused by the generator or used for other purposes. Refdinal et al. has developed an ELC system that can optimally utilize generator output power [9,17]. The dummy load, which initially used a resistive load, was then replaced with a battery, as shown in figure 3. The battery here acts as an energy storage medium so that the excess power can be stored to be used for various other purposes.

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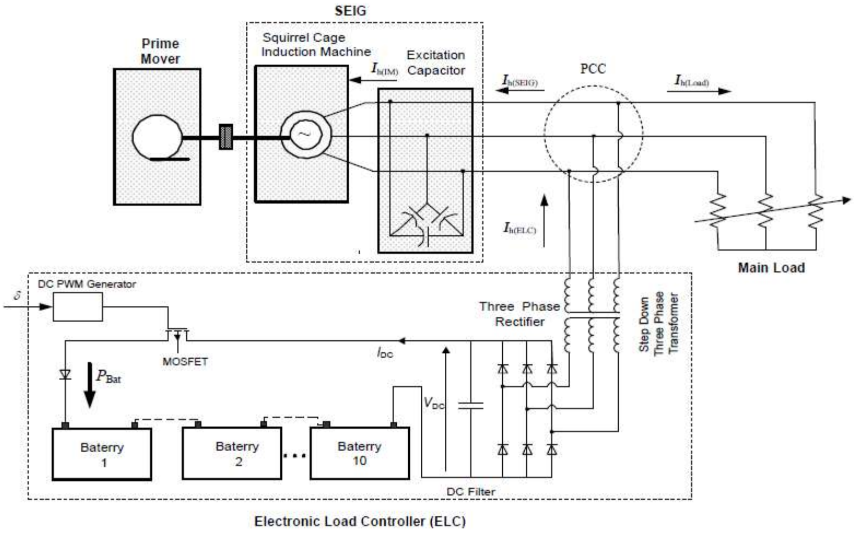

Figure 3. The configuration of ELC with DC chopper and battery dummy load

ELC with Bidirectional Converter and Battery Dummy Load

The ELC DC Chopper with dummy load battery discussed in section 2.2 still has several drawbacks. If the battery is fully charged, the battery must be replaced with an empty one so that the ELC system can continue to run according to its function. This condition is impractical in its operations and uneconomical in its financing. In this study, an ELC system with bidirectional converter and dummy load batteries was developed.

A bidirectional converter is a converter that can be operated to supply power in two directions, which means it can operate as an inverter or rectifier. Bidirectional converters can operate on the principle of a voltage source rectifier (VSR) or a voltage source inverter (VSI). VSR is a rectifier that can adjust its output voltage independently[18-19]. Meanwhile, VSI is an inverter that independently keeps the output voltage stable [20]. Usually, the two converters are included in the voltage source converter. The difference between these converters generally lies in the control side of the output, the DC side voltage is regulated, while the AC side voltage is regulated in VSI. In the study, the VSR principle was applied with the PWM method. The PWM VSR is operated by controlling the input current, as can be seen in Figure 4.

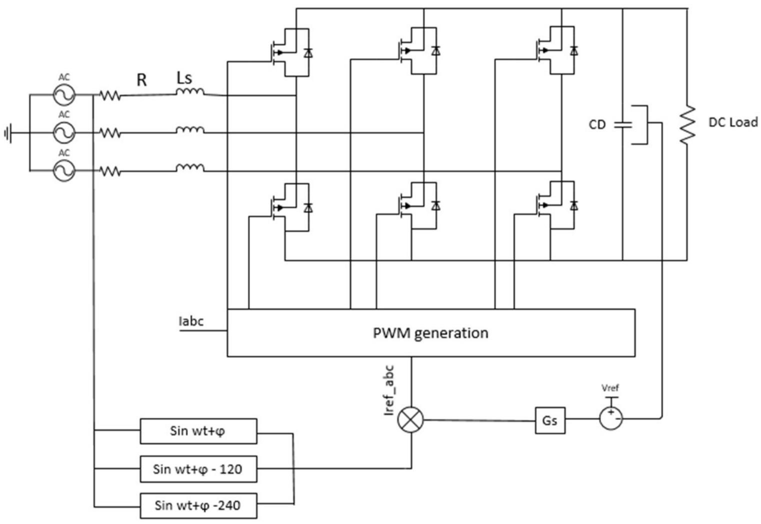

Figure 4. PWM Rectifier with current control

In this system, the input current is controlled depending on the load changes on the DC side, and the measured current is forced to follow the reference current. The reference current is obtained from the difference between the DC reference voltage (Vref) and the DC measured voltage (VDC). The reference voltage is set higher than the diode voltage (VBRIDGE), it is intended to make

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the work of the PWM VSR not the same as an ordinary rectifier. PWM VSR can flow power in two directions. The method to regulate the power flow in PWM VSR is to adjust the reference signal amplitude, shift the reference signal phase angle and change the shape of the switching signal [18]. By applying the concept of a bidirectional converter to the ELC system, it will made the power flow to the generator can be further optimized. Power that would otherwise be wasted can be stored and reused. In this system, the battery is used as a dummy load.

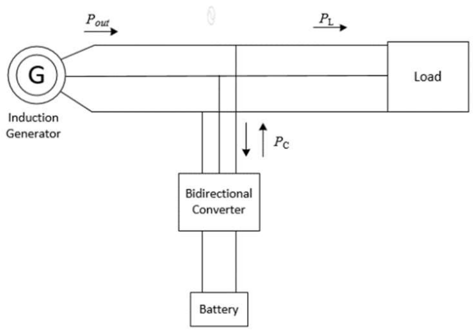

Figure 5. ELC with bidirectional converter and battery dummy load

This developed ELC can work in 2 conditions: (1) the generator output power condition is greater than the load power, and (2) the generator output power condition is smaller than the load power. For both conditions, the work of the developed ELC can be explained by Figure 3. When there is an excess of generator output power, the converter will supply power to the battery by changing the working operation of the converter into a rectifier. Meanwhile, the battery will also supply power to the load when the generator output power is less than the load power. In this stage, the converter will transfer power from the battery to the load by changing the working operation of the converter into an inverter. The battery will function as a load when the generator output power flows to the converter and battery, and vice versa the battery will act as a source when battery power flows to the converter and load.

System Design of Developed ELC

Figure 6 shows the system design of the ELC with a bidirectional converter and a dummy load battery. As the figure shows, the bidirectional converter uses a PWM VSR with current control. As previously explained, PWM rectifiers can transmit power in two directions (bidirectional). In addition, the schematic of the control of the PWM rectifier through the management of current and power flow in this system is also shown. Figure 6 also shows a control method for adjusting the output voltage by comparing the measured voltage with the reference voltage. The difference in voltage *e* will be processed by the PI control to be used as the maximum current value. This maximum current value will be synchronized with the source to be used as a reference current. The smaller amount of *e* will provide a more stable resulting output. The phase angle shift method on the reference signal is used to adjust the amount of power flow in the converter. The magnitude of the shifted phase angle is obtained based on the error between the reference frequency and the measured frequency. The PI control processed the error to be used as a large value for the phase angle shift [21]. In controlling the output voltage, the values of Kp = 2 and Ki = 2.8 while on the frequency control, the values of Kp = 2 and Ki = 100. The values of Kp and Ki are obtained by the trial-and-error method. The *R* component in the design system above represents the line resistance. In contrast, the L component to representing the line inductance is also equipped with an *L* component as a filter, especially for filtering high-order harmonic current components.

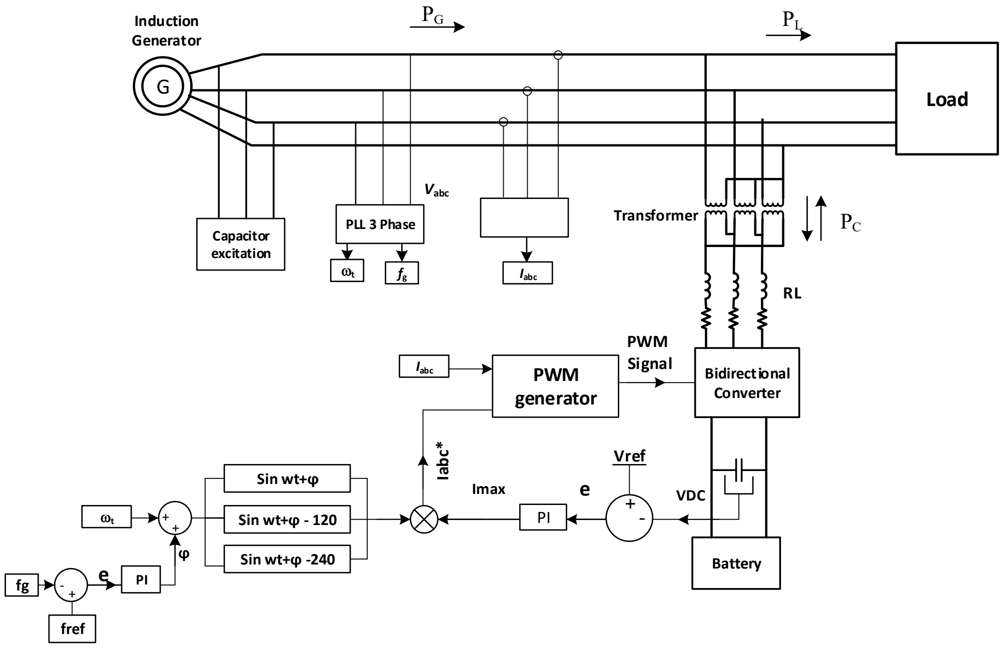

Figure 6. System design of ELC developed

Simulation Circuit

The design system from the ELC developed in session 3.1 is implemented in a simulation circuit. Figure 7 shows a simulation circuit of the ELC with a bidirectional converter and a dummy load battery. The simulation process is run using MATLAB software. The main variable observed in the simulation test is frequency. In SEIG, frequency changes can significantly affect the voltage, while voltage changes almost do not affect the frequency. In this test, the load system is considered to be in equilibrium, and its constructed by purely resistive components.

In this study, there are two simulation tests. It consists of the simulation test of the frequency regulation of the generator and the simulation test of the close loop response of the ELC developed during load changes. In the simulation test of the frequency regulation, the generator is set at a frequency of 50 Hz with a total load of 985 Watt. The torque value under these conditions is recorded. Then the load is set to 955 Watt, 985 Watt, 1015 Watt, and 1045 Watt with the torque value in the previous condition. The interval between load changes is set 1 second for each load with an interval of 5 seconds. The output frequency for each of these loads is recorded.

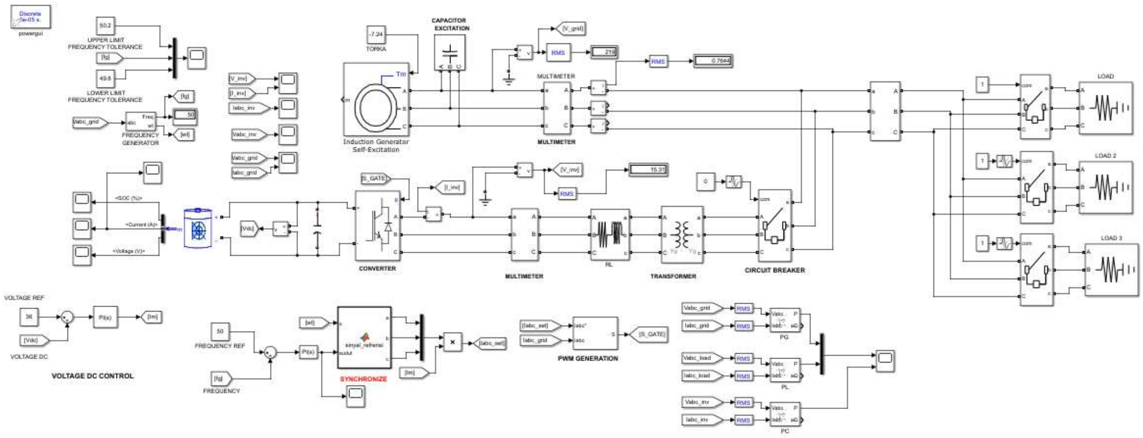

Figure 7. The simulation circuit for SEIG with ELC developed

In the closed-loop test, the ELC developed is installed in parallel with the generator, then the generator torque is set constant with the value obtained previously. Loads are set to 955 Watts, 985 Watts, 1015 Watt, and 1045 Watts. The generator output frequency is recorded and then compared with the previous experiment. If the generator frequency has stabilized in the tolerance area (49.8 – 50.2 Hz), the system has succeeded in working according to the expected standard.

RESULTS AND DISCUSSION

Simulation Result of Frequency Regulation During Load Change

Figure 8 is a simulation result, which shows the variation of the generator output frequency during changes in the load powers. As shown in Fig. 8, several conditions cause the frequency value to exceed the tolerance limit when the load is varied. The safe area for frequency varies based on applicable standards is 49.8-50.2 Hz [22]. If it is less or more than that value, under or over frequency will occur. From these data, there has been over frequency and under frequency in the induction generator. This data will be compared with the test results in the following session.

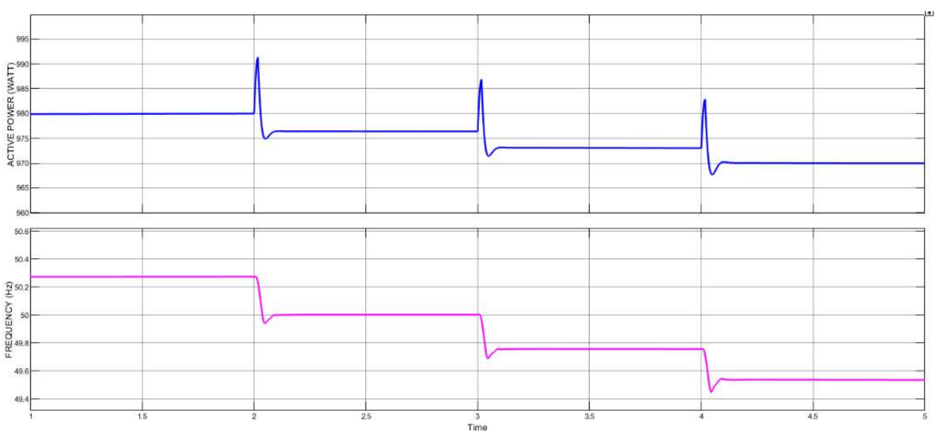

Figure 8. The output frequency of SEIG during load variations

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Simulation Results of Close Loop Response of SEIG developed

The simulation results show that installing ELC with a bidirectional converter can stabilize the generator's frequency in the value range of 49.98 – 50.01 Hz for the same load variation. This condition can be seen in Fig. 9. As shown in the figure, after the generator is connected to the ELC developed, SEIG immediately returns the frequency to a safe area or within tolerance limits when over and under frequency occurs. When the frequency value exceeds the maximum allowable frequency limit value (50.2 Hz), the system immediately returns the frequency to the allowable tolerance value range. Likewise, when the frequency value is lower than the minimum allowable value. This applies by changing the function of the converter into an inverter and rectifier. If an over-frequency converter acts as a rectifier, power will flow from the generator side to the converter side and then be absorbed by the battery. When over frequency occurs, the battery will be the source and supply power to the load. In this condition, the converter will act as an inverter, and power will flow from the converter side to the load side. The over-frequency condition occurs when the generator is loaded with 955 Watt. When this condition is reached, the generator immediately returns the frequency to the tolerance area. The time needed to return the generator to the tolerance area or steady-state condition from when the system responds to changes in frequency is 0.4 seconds. Meanwhile, when under-frequency occurs when the generator is loaded with 1015 watts and 1045 watts, the time required by the generator to return the frequency to a steady-state condition is 0.1 seconds. When the generator is loaded with 985 Watts, the frequency is in the tolerance area, so the system only optimizes the frequency value in this condition to 50 Hz.

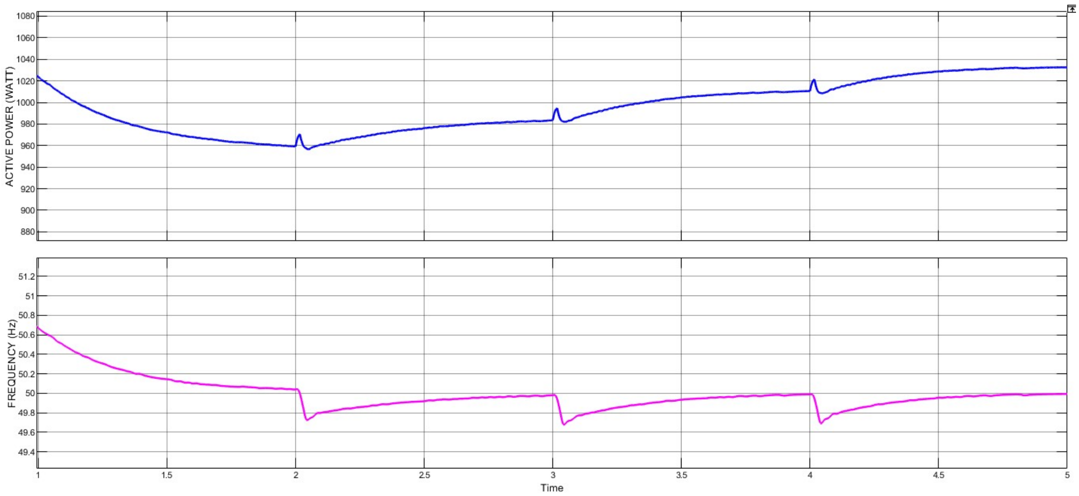

Figure 9. The simulation results of close loop response of SEIG developed

As also shown by figure 10, the power delivered to the load corresponds to the power required by the load. This proves that the system is working properly. When there is an over-frequency condition, the generator will be overloaded. The converter will absorb the power. The power absorbed by the load represented by the yellow graph is less than the generator output power represented by the blue graph. Likewise, when there is an under-frequency, the power absorbed by the load is greater than the power generated by the generator. The above argument is strengthened by the current flowing in the battery, as shown in figure 11. Referring to the characteristics of the battery, when the battery is charging, the current in the battery will be negative. In contrast, the battery current will be positive in the discharge condition. Changes in the polarity of the current flowing in the battery will indicate the battery is in a state of absorbing or delivering power.

Discussion

From the simulation results, the generator frequency is stable in the range of 49.98 – 50.01 Hz frequency values. This value is still within the recommended tolerance limits. When the frequency exceeds the tolerance limit, the system immediately returns the frequency to a safe area. The graph of the pattern of frequency changes obtained from the test results is similar to previous studies[23-25]. Changes in current polarity and power absorbed by the load also indicate that this system has been working properly[17,25].

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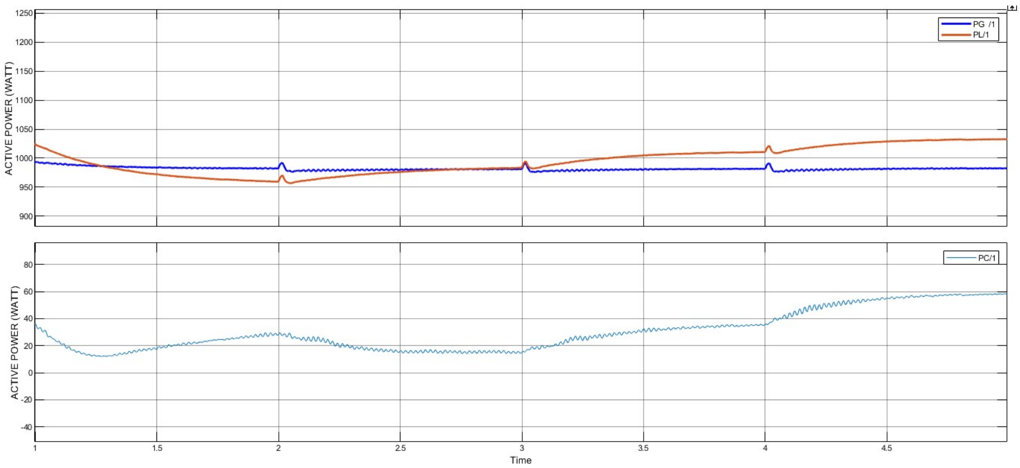

Figure 10. The power changes in generator, load, and converter

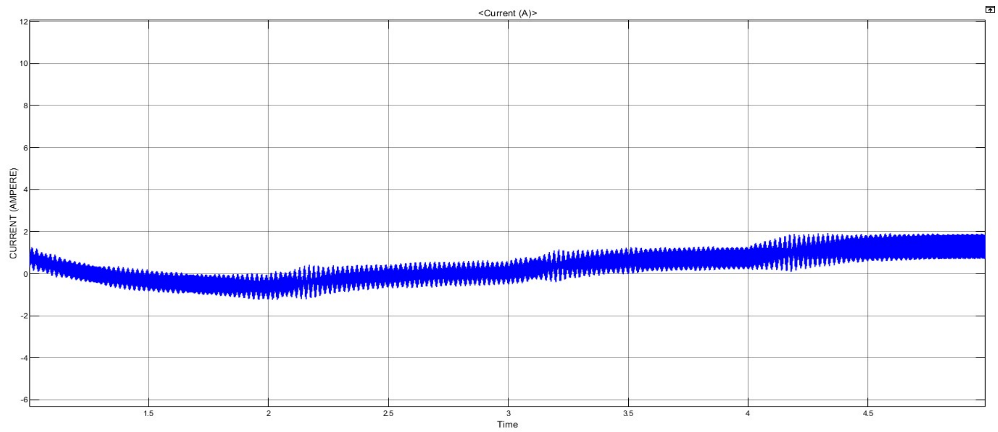

Figure 11. The current change in battery

CONCLUSIONS

Based on the simulation results, this system can adjust the generator frequency in the value range of 49.98-50.01 Hz when there is a load change in the range of 955 Watt to 1.045 Watt. It can be solved by setting the active power flow on the SEIG. Using an ELC system with a bidirectional converter and a dummy load battery, the frequency setting on the SEIG becomes more optimal. Excess power can be stored and reused when the load requires it in this system.

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