

Energy Saving Analysis and Simulation for Home Electricity

Nader Barsoum, Farah Talib

Department of Electrical and Computing Engineering, University of Sabah, Kota Kinabalu, Malaysia

Email: nnb3@hotmail.com

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Abstract

This paper presents the energy saving method by applying the voltage control technique on a single-phase AC source to a thyristor rectifier and an IGBT inverter with LC filter. Based on the LC filter parameter, the values of the gain for the controller are obtainable. The proposed controller structure consists of two loops arranged in a cascaded model. The output of the first loop is the capacitor current. This current is added to the load current in order to obtain the current reference. This reference current value will be compared with the inverter current which produces the error signal to be fed into the second loop in the cascade system. The output of the second loop is the inverter voltage. This voltage is added to the load voltage to produce the voltage reference. This reference is fed to the pulse width modulation generator via the controller and compared with the triangular wave. This energy-saving circuit is designed in blocks using MATLAB Simulink.

Keywords

Energy-Saving Circuit, Rectifier-Inverter, LC Filter, PI And PR Controllers, MATLAB/Simulink

1. Introduction

Based on the formula of power equation, power is the rating when the work is done. Precisely power-time is equal to the energy consumption where the unit is in watt-hr. From the formula of power, current and voltage are obtainable. These values have a functional relationship where when any change in one variable the other variable changes while the power is constant. The voltage rating for domestic household in most countries is 240 V. The value of voltage is constant while the value of current flow is varying with time. There are many other factors affecting the total power consumption including the power rating of the

load.

Lighting system in house is the easiest example to understand this matter. There are so many different ratings for the bulb. For example, there are two bulbs with the same material having a different power rating. Since the voltage in the house is constant, the bulb with the higher rating will draw more current compare to the other one in order to achieve the same luminance level. Hence, using the high-power rating bulb will consume more energy which leads to the increase of electricity bills.

The current is determined by the rate of change of the charge with time. When relating the power to electric energy, the voltage is the potential difference by the movement of the charge over certain amount of time. The electric energy is given by the power consumption for a time interval. This formula can be used to illustrate the electric energy used in the house. For example, the more lightbulbs burning, the power consumption is increasing [1]. When turning on the bulb, the time interval will keep increasing until the bulb is turned off again. From this situation, it can be proved that when the working time for the appliance is increased, the electric energy used is also increased. The used energy can be minimized simply by reducing the time of usage, or by decreasing the power of the appliance. An improvement in lighting system is one of the finest methods of managing the power consumption for a house.

Lighting plays a big role in energy consumption. However, this statement depends on the usage time which means the longer the time to use the bulb the more energy is consumed. Another aspect also can impact this statement which is the type of the bulb use in the house. The numbers of halogen or energy-saving light bulb were not significant in consuming the electrical energy [2]. Approximately 20% of the energy consumption of a house is from the lighting system; meanwhile for commercial establishments, the percentage is closer to 40% [1]. Compare to other electric appliances in the house, specific appliances such as refrigerator, heater and air-conditioner consume more energy for the minimum electricity consumption [2].

The research here is focused on reducing the energy consumption of the appliance when are used for a long time. The method of reducing power as an alternative way of the method of reducing time used is discussed in this paper. Since the power depends on current and volt and the current is variable while the voltage is constant, then variable voltage is considered to save the energy consumption. This can be done by controlling the voltage during high power rate used in the house. The controller is connected to a rectifier-inverter circuit attached to the main circuit breaker of the house main board before the fuses set.

Power inverter is used for DC/AC conversion however it is a nonlinear device where IGBT (Insulated Gate Bipolar Transistor) produces the sinusoidal waveform. The non-linear device contains harmonic which will cause the system less efficient [3]. To implement the energy saving circuit containing the non-linear device such as thyristor and IGBT, a suitable filter must be used in order to re-

duce the harmonic from the high frequency device. The power supply for the house must be stable for the appliances to function properly. Unstable power source will cause the appliances to defect faster. Reducing the voltage value will decrease the power and hence to save the used energy. In order to achieve this, voltage controller is designed.

In this paper, a circuit which can save the energy by regulating the power consumption and controlling the load voltage value is designed. The designed circuit is named as energy-saving circuit which consists of rectifier-inverter and a voltage controller. Since IGBT is used in a single-phase inverter design hence pulse width modulation generator is required. The parameter of the voltage controller is obtained through the LC filter parameter which is implemented at the output of the single-phase IGBT parameter. Evaluating the parameter values of voltage controller that cause the input voltage to the load is formulated to obtain some desired value. The paper also shows the design of the AC filter for the inverter in order to eliminate the voltage ripple and harmonic distortion caused by the high frequency device. Finally, the analysis and simulation of energy saving circuit containing a voltage controller are done by MATLAB Simulink software [4].

2. Rectifier-Inverter of Energy Saving System

Single-phase thyristor rectifier consists of 4 thyristors [5] which place or have an arrangement of H-bridge in the circuit. Single-phase rectifier is also known as the full wave bridge rectifier connected in a closed loop bridge configuration. This single-phase thyristor rectifier will convert the AC power supply to the DC form. The four thyristors are working in pair to become forward biased and reverse biased. This DC output from the rectifier can be improved by implementing the smoothing capacitor. This smoothing capacitor is important as it can allow the switch mode power supply circuit to operate correctly [6].

The single-phase inverter consists of four IGBT. From the switch leg number, the type of inverter can be identified where the half bridge inverter will only consist of two switch leg meanwhile for the single-phase full bridge inverter consist of four switch leg. The single-phase full bridge is also known as H-bridge inverter. H-bridge inverter configuration is chosen because of its simplicity and elevated effectiveness [3]. The output current and voltage at full bridge rectifier is twice when compared to the half bridge inverter and harmonics is doubled in the full bridge due to this, the output current is smoother and has better quality [7].

Pulse width modulation generator is used to generate pulses for the IGBT inverter in the circuit. The signal comes from digital sources to have two states ON or OFF. Usually, 1 is the indicator of the ON state, while 0 is for OFF state. Techniques using PWM play a crucial role in managing power electronic controllers [7].

LC filter is used at the output of the inverter to eliminate the distortion causes

from the high frequency non-linear device. LC filter is consisting of inductor and capacitor where inductor acts as short circuit and capacitor acts as open circuit. The value chosen for this filter is based on the required design. Even with small L and C values, LC filter can provide a decent attenuation ratio [8]. The value of inductor can be obtained from the formula of current ripple and derivation of the basic ohm's law for the inductor meanwhile for the capacitor the value is obtainable from the cut-off frequency or also known as resonant frequency. LC circuit can store energy, which oscillates at its normal resonant frequency.

It is given in [9] that the output of the PI controller is directly proportional to the combination of absolute error with the integral of the error signal. The absolute error is the part of the proportional control meanwhile the integral of the error signal is the part of integral controller. The relationship between the output and input of the PI controller can be written as in equation (1):

$$U(t) \propto e(t) + \int e(t)$$

$$U(t) = Kp e(t) + Ki \int e(t) \quad (1)$$

$U(t)$ = output of the PI controller;

$e(t)$ = absolute error;

Kp = gain for the proportional controller;

Ki = gain for the integral controller.

In order to obtain the transfer function (2), LaPlace transform is applied to the formula (1).

$$U(S) = KpE(S) + Ki \frac{E(S)}{S}$$

$$U(S) = E(S) \left(Kp + \frac{Ki}{S} \right) \quad (2)$$

The transfer function of PR controller is derived from the ideal synchronous frame PI controller to stationary setting which will give the infinite gain at the alternating current of ω_0 [8]. In PR controller, the steady-state error becomes zero and the phase shift and gain are removed at other frequencies. The transfer function of PR controller is represented by Equation (3):

$$G(S) = Kp + \frac{(Ki)S}{S^2 + \omega_0^2} \quad (3)$$

ω_0^2 = resonant frequency.

3. Energy-Saving Circuit

There are two types of energy saving circuit that have been designed. Both of the circuits have the same technique which detecting the amount of current and voltage that flow to the load. For the first design the controller implemented to the circuit is PI controller while the second design is PR controller, the equipment needed are voltage sensor to detect the load voltage, two current sensors to

detect the inverter current and load current, voltage reference, comparator, single-phase IGBT inverter and single-phase controlled rectifier. The difference between PI and PR controller is that the PR has additional negative feedback loop which will improve the performance of the controller [10].

In this paper, the circuit is designed by using the tools from MATLAB Simulink library. As the source of the energy saving circuit, the 240 AC Volt household outlet is rectified and the value of voltage is expected to be 216 DC Volt. This can be proven by using formula (4):

$$VDC = \frac{2}{\pi} \sqrt{2} * Vrms = 0.9 * 240 = 216 \text{ V} \quad (4)$$

The voltage peak-to-peak value for 240 V can be calculated by using the formula (5):

$$Vpp = \sqrt{2} * Vrms = \sqrt{2} * 240 = 339.41 \quad (5)$$

After the rectification, the input voltage for the IGBT inverter is equal to 216 V. The DC value is then converted again to AC form by the single phase IGBT inverter for the home load that requires an AC source. The purpose of the rectification is to give the DC input signal for the controller. Next, at the output of the inverter, an AC filter is implemented in order to reduce the harmonics from high frequency component. In this paper, the filter used is LC filter which consists of inductor and capacitor. The parameter for these components is used to obtain the gain for the controller.

The formula used to obtain the desire value of the filter is derived by the basic ohm's law for inductor and cut-off frequency for the capacitor. After obtaining the value of the filter, the gain for PI and PR controller is designed. For PR controller there will be an additional negative feedback loop in which will help to give a proper output compare to the PI controller.

For the inductor design, the formula across the inductor can be expressed as shown in Equation (6). Rearranging and substitute the equation of duty cycle (7) into Equation (6) will provide the final equation for the inductor design (8). The designed inverter has 216 V as an input which is the value of VDC. Meanwhile the value of voltage output for the inverter will 240 V and the frequency will be the same as 50 Hz. The power output for the inverter is 2000 W and the switching frequency is equal to 10 kHz while the inductor current is assumed lower than 20%. After substituting all the data to Equation (8), the value of inductor designed is 2.29 mH.

$$VDC - Vout = L \frac{I_{ripple}}{DTs} \quad (6)$$

$$D(wt) = ma * \sin(wt) \quad (7)$$

$$L = \frac{VDC}{4(Fs)I_{ripplemax}} \quad (8)$$

Calculation of the inductor design:

$$I_{ripplemax} = \left(\frac{2000}{240} \right) \sqrt{2} (0.2) = 2.357$$

$$L_i = \frac{VDC}{4(Fs)I_{ripplemax}}$$

$$L_i = \frac{216}{4(10000)(2.357)} = 2.29 \text{ mH}$$

For the capacitor design, as mentioned before, the value of the capacitor for the filter can be obtained through the formula of cut-off frequency (9). In order to obtain the preferable value of switching frequency, the value of the cut-off frequency should be lower or equal to the value of switching frequency, F_s divided by 10. The value of capacitor for the filter can be obtained after attenuating Equations (10) and (11).

$$F_c = \frac{1}{2\pi\sqrt{LC}} \tag{9}$$

$$\frac{F_s}{10} = \frac{1}{2\pi\sqrt{LC}} \tag{10}$$

$$C = \left(\frac{10}{2\pi F_s} \right)^2 \frac{1}{L} \tag{11}$$

Calculation of the capacitor design:

$$C = \left(\frac{10}{2\pi(10000)} \right)^2 \frac{1}{2.29 \text{ mH}} = 11.06 \text{ }\mu\text{F}$$

There are two parts in the PI controller the first calculation shows the gain of the voltage controller and the second calculation is for the gain of current controller. For voltage controller, the time constant is 200 μs meanwhile the time constant for current controller is 150 μs . The time constant of the controller is used to determine the speed of the controller. The PI controller structure consists of two loops arranged in a cascaded model. The output of the first loop is the capacitor current. This current is added to the load current in order to obtain the current reference. This reference current value will be compared to the current from the inverter producing the error value to be fed into the second loop in the cascade system [11].

The second loop will give an output of inverter voltage. The load voltage is then added to the inverter voltage which producing the reference voltage. This value is fed into the unipolar pulse width modulation generator where the reference current from the controller is compared to the triangular wave. The gain for the controller can be obtained through Equations (12) and (13) where the (equivalent series resistance) ESR value is referred to the data sheet [12].

$$K_p = \frac{\text{Filter Capacitance}}{\text{time constant, } tc} \tag{12}$$

$$K_i = \frac{\text{Equivalent Series Resistance}}{\text{time constant, } tc} \tag{13}$$

Calculation of the gain for the voltage loop of the PI controller:

$$K_p = \frac{11.06\mu}{200\mu} = 0.0553$$

$$K_i = \frac{0.0042}{200\mu} = 21$$

Calculation of the gain for the current loop of the PI controller:

$$K_p = \frac{2.29m}{150\mu} = 15.267$$

$$K_i = \frac{0.001}{150\mu} = 6.67$$

The load voltage wave from PI controller is shown in **Figure 1**, and for PR controller is shown in **Figure 3**.

Figure 1 shows the waveform of the load output voltage for PI controller which connected to the inverter circuit only.

Using PR controller, for the proportional gain, the same formula of the PI controller is used. This is because the changes in PR controller only occur at the integral part whereas an additional negative feedback loop for the harmonic compensator is added to the design as shown in **Figure 2**. This negative feedback loop will improve the performance of the controller. The controller is designed with the resonant frequency of 314.16 radians per second.

Equation (14) shows the gain for the PR controller. From the equation, the starting value of K_i can be obtained by letting the gain equal to 0.1 [13]. The starting value for K_i is equal to 627.2. To tune the controller, the value of the K_i is reduced until the proper voltage output is obtained. From the calculation, the K_i value chosen for the controller is 100 for the voltage loop and 400 for the

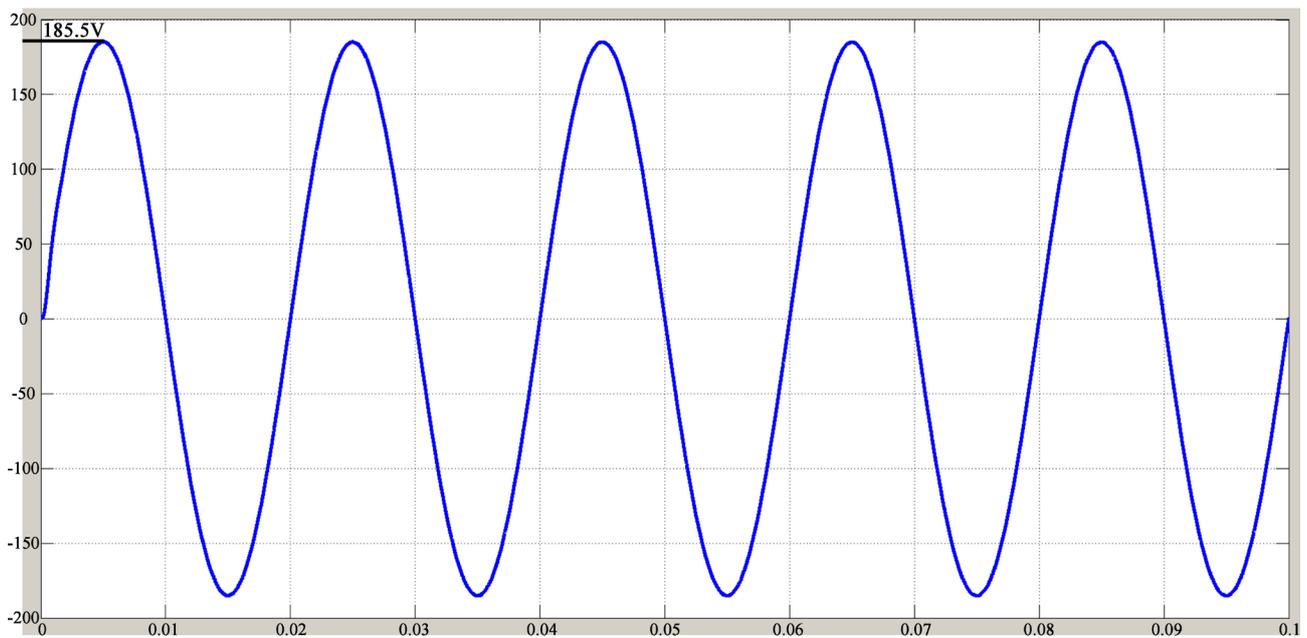


Figure 1. Waveform of load voltage from PI.

Table 1. The 2 loops gain and output voltage.

Voltage loop		Current loop		Output voltage (V)
Kt	$\frac{\omega^2}{ki}$	Kt	$\frac{\omega^2}{ki}$	
627.2	157.36	627.2	157.36	202.56
100	986.83	400	246.7	190.00

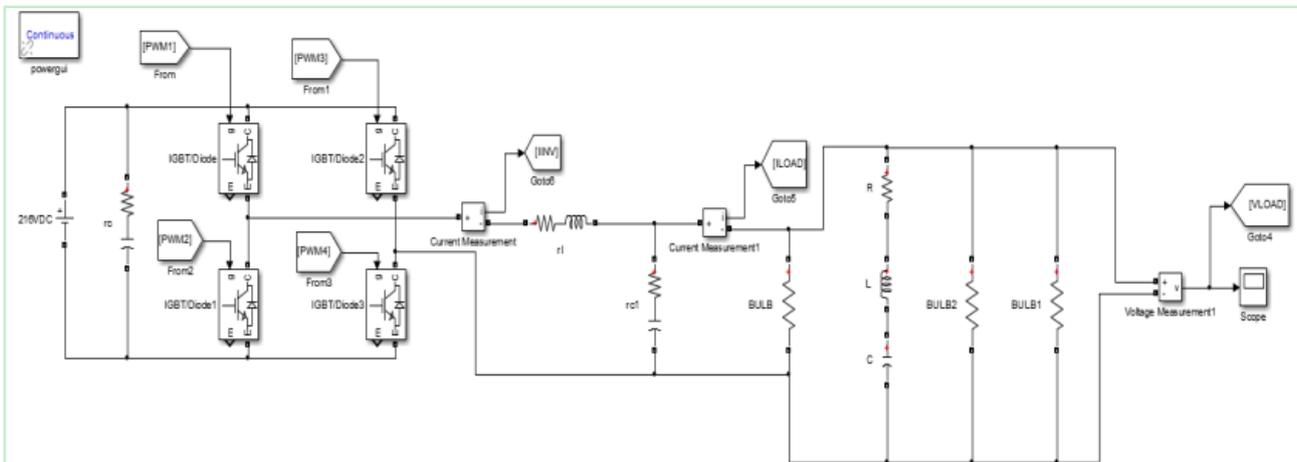


Figure 4. IGBT Inverter with load circuit only.

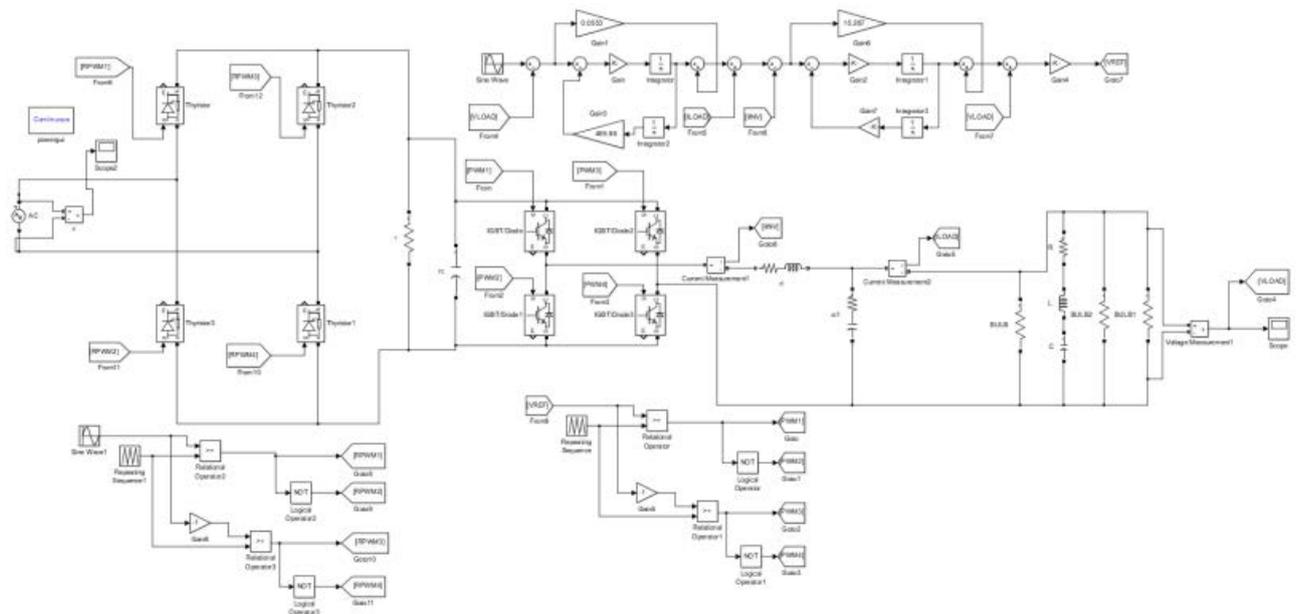


Figure 5. Energy-saving circuit with closed-loop PR controller.

is connected to the smoothing capacitor with Equivalent Series Resistance, ESR. The value of the capacitor is 236 microfarads and the value of ESR is 0.0042 ohms. LC filter shown in **Figure 6** is implemented at the output of the inverter for filtering the high frequency component or limiting the rate of rise of the inverter output voltage and reduce common mode noise. The closed-loop PR con-

troller needs three sensors. The first sensor is located at the load to get the voltage output. The second sensor is for the inductor current which equivalent to the inverter current. The last sensor is for the load current. In order to find the absolute error for the PR controller shown in Figure 8, the load voltage value is needed. This value is found from the block of the voltage sensor measurement that connected to the load as shown in Figure 7 and fed to the comparator. At

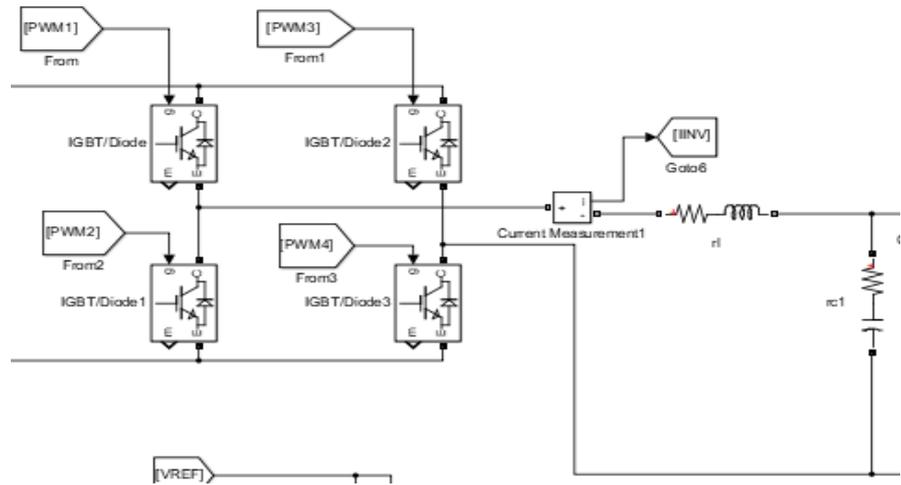


Figure 6. Inverter and LC filter in MATLAB.

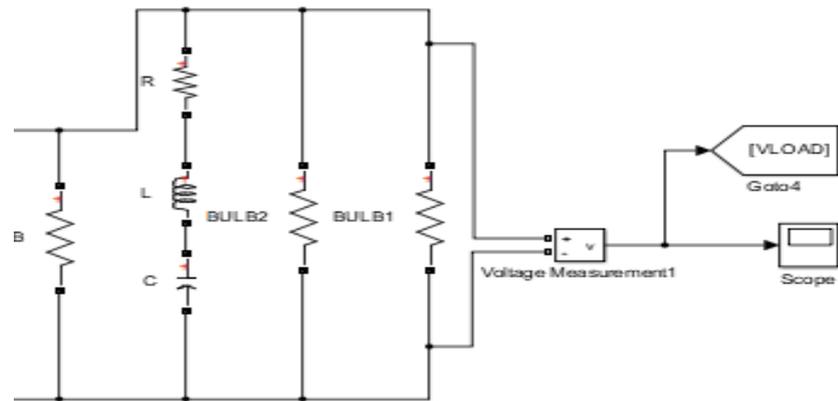


Figure 7. Load circuit with voltage sensor measurement.

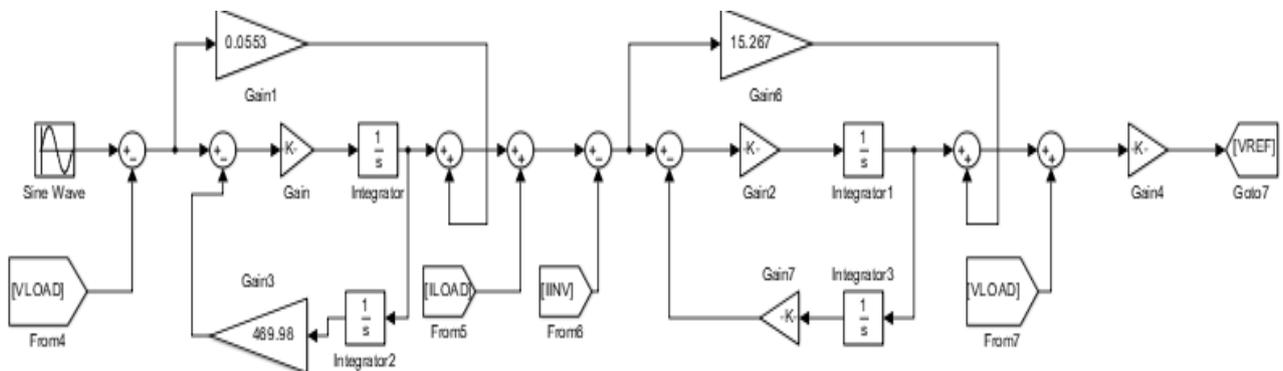


Figure 8. PR controller block in MATLAB.

the comparator the value of load voltage is compared to the voltage reference which producing the absolute error for the PR controller. Sine wave block is used to give the voltage reference value. The amplitude of the sine wave at the PWM inverter generator is the voltage reference for the PR controller. The frequency required by the sine wave block is in rad/sec [13].

The absolute error is then fed into the voltage loop of the PR controller. The output of the PR controller is the capacitor current. The capacitor current is added to the load current by using the “sum” block. According to Kirchhoff’s law, the output of this calculation is the inverter current. This output value is compared to the real inverter current from the second sensor in order to get error signal for the current loop of the PR controller.

The output of this controller will provide the voltage across the inductor. After adding the load voltage and inductor voltage by using “sum” block, the value of inverter voltage will be obtained. This value is equivalent to the reference voltage which will be inverted by the generator and fed to the PWM generation block. The inductor or inverter current of the filter acts as an inner loop parameter while the output voltage is the outer loop parameter [11]. For the PWM generation block shown in **Figure 9**, the reference voltage is compared to the triangular carrier wave. Both positive and negative voltage reference are compared by using the comparator. Each output of the comparator is fed into the IGBT by using “From” (**Figure 6**) and “Goto” (**Figure 9**) blocks which connect the output of the PWM generator to the IGBT. These blocks connect two points without using a physical wire. The blocks are labelled according to the desired destination.

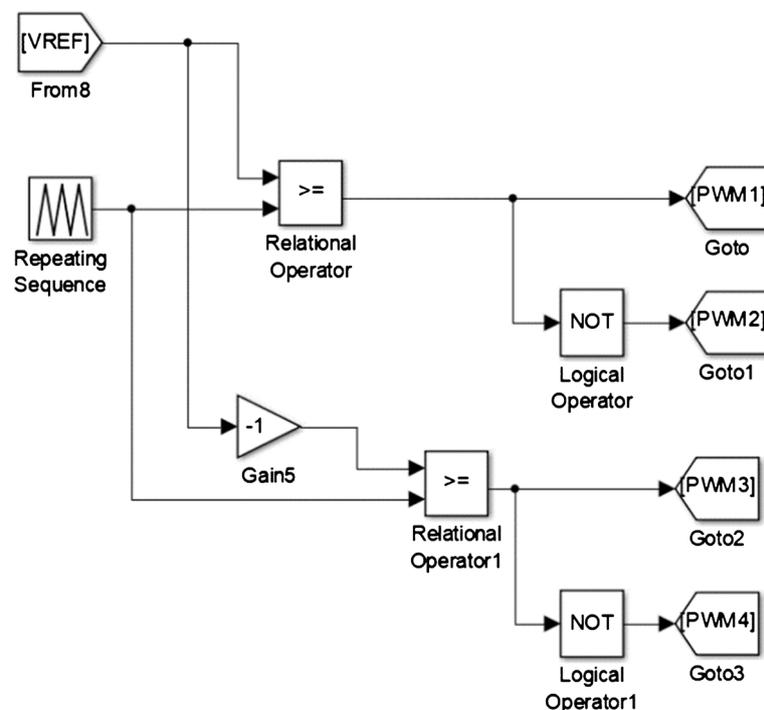


Figure 9. Unipolar PWM generator block.

From **Table 2**, in order to achieve 185 V voltage output Ki value of the voltage loop is reduced to 210 and the Ki value for the current loop is reduced to 280.35. The gain value of the PR controller has been changed when combining the rectifier circuit to the inverter circuit. This happens due to the unstable output comes from the rectifier. **Figure 10** shows the output voltage for the energy-saving circuit.

In **Figure 3**, the load output voltage for PR controller has Ki for voltage loop equals 210 and Ki for current loop equals 280.35.

The next part shows the MATLAB simulation and circuit analysis for the load circuit (RLC, 1.0 hp air-condition), **Figure 10**.

Figures 11-13 show the 3 curves of voltage in RLC circuit of 1 hp air-con when zooming **Figure 10** to see the peak values of the voltage across each component.

Table 2. Ki and gain values for additional negative feedback in the PR controller.

Voltage loop		Current loop		Output voltage (V)
Ki	$\frac{\omega^2}{ki}$	Ki	$\frac{\omega^2}{ki}$	
627.2	157.36	627.2	157.36	202.56
100.00	986.83	400.00	246.70	190.00
112.62	876.31	356.11	277.15	189.5
130.00	759.20	350.00	281.99	188.00
170.00	580.57	280.35	352.49	186.78
190.00	519.45	280.35	352.49	186.52
210.00	469.98	280.35	352.49	185.54
270.00	365.54	400.00	246.74	220.00

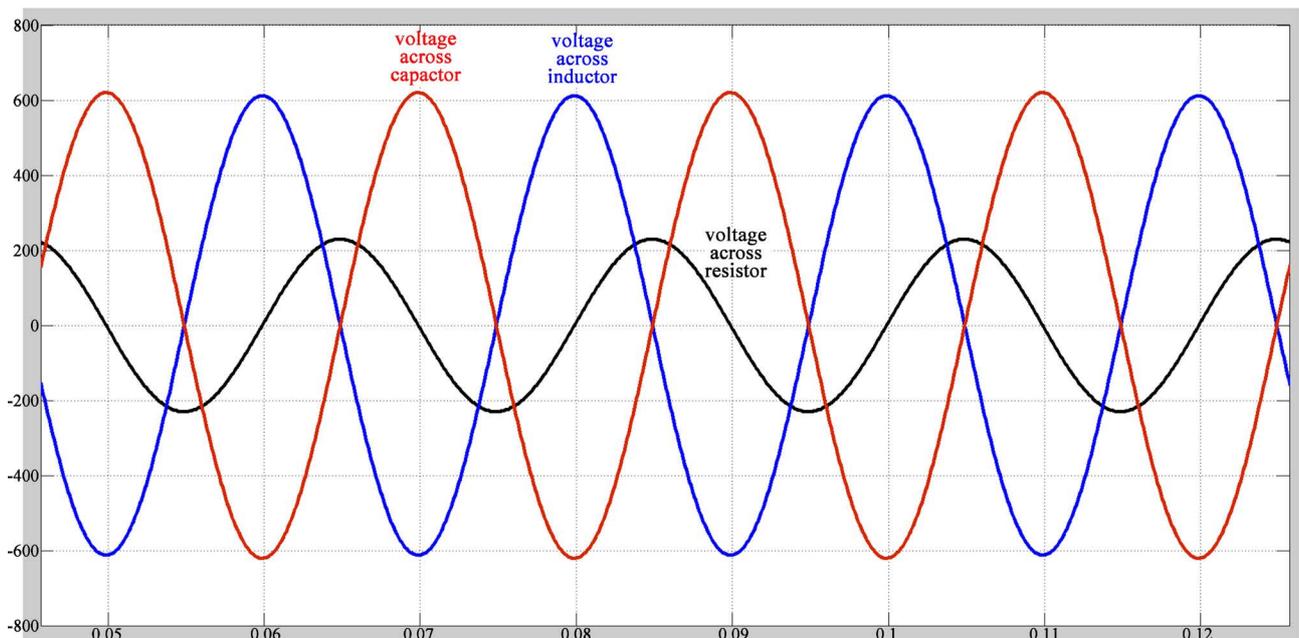


Figure 10. The simulation result for RLC Circuit (1.0 hp air-con).

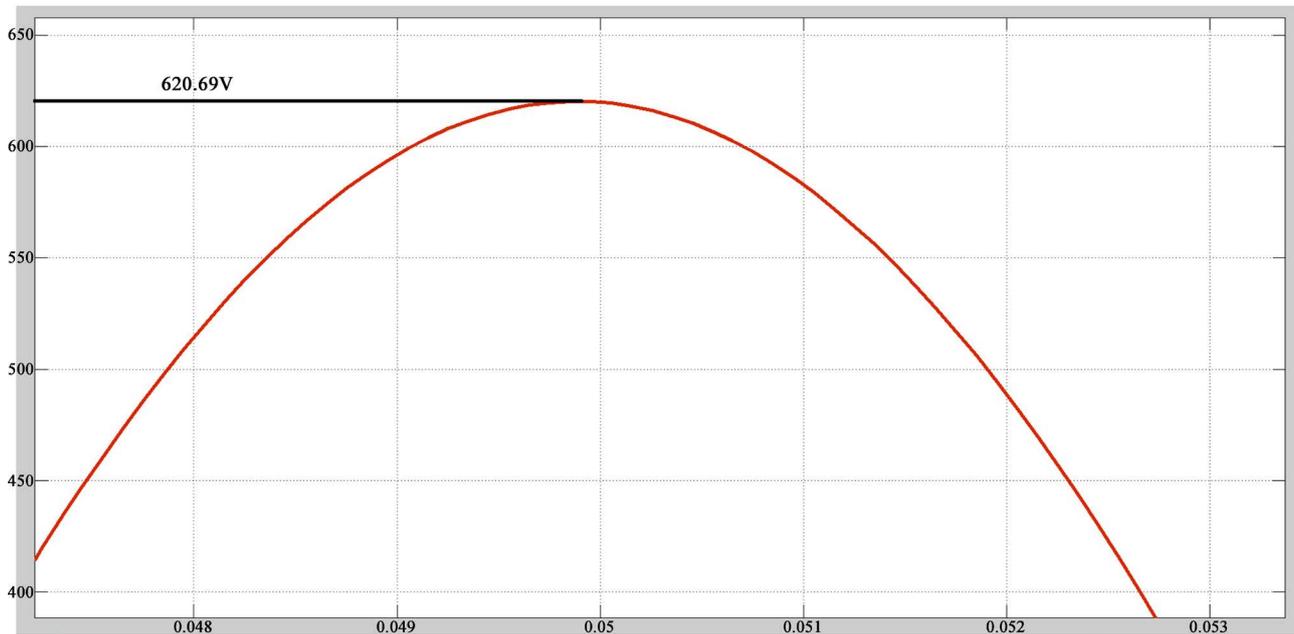


Figure 11. Voltage across capacitor = 620.69 (Zoom in).



Figure 12. Voltage across inductor = 612.61 (Zoom in)

The process of this simulation is done by filling the Simulink block menus as shown in [Figure 14](#).

The value of resistance is calculated from the air-con datasheet where the running voltage is 230V and current is 3.9 A. Using the ohm's laws, the value of R is obtainable. In order to verify the value of voltage across each component, circuit analysis is done.

Where from air-con datasheet:

$$R = 58.97 \Omega, L = 500 \text{ mH}, C = 20 \mu\text{F}$$

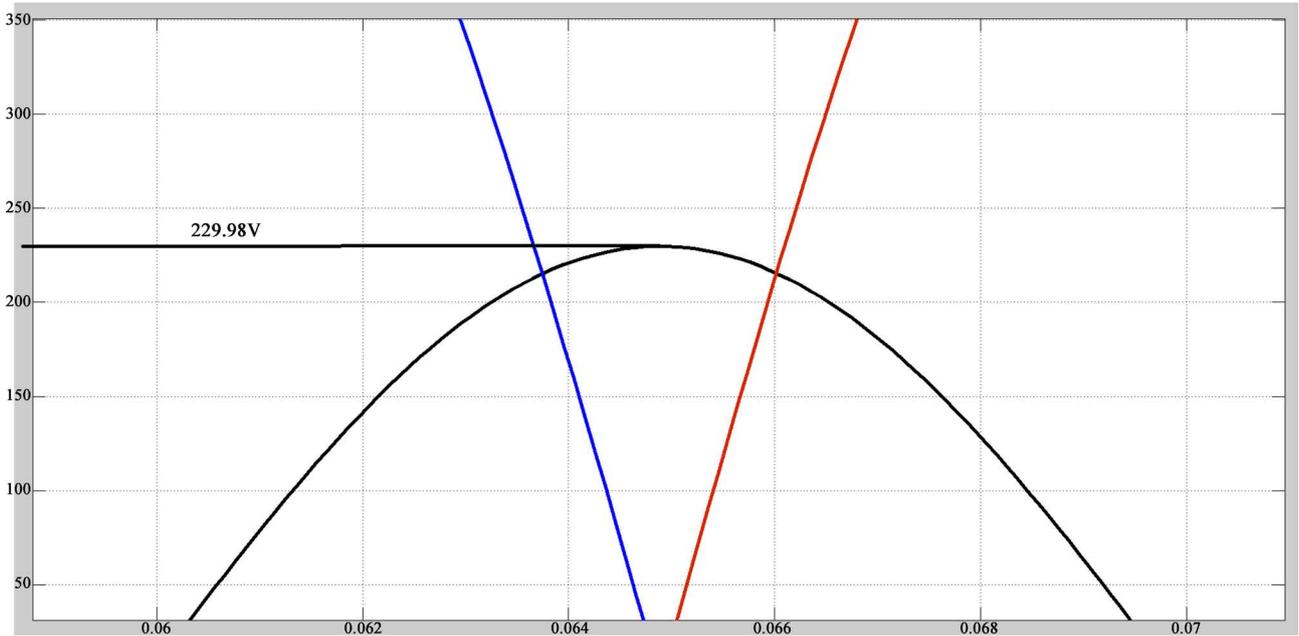


Figure 13. Voltage across resistor = 229.98 (Zoom in).

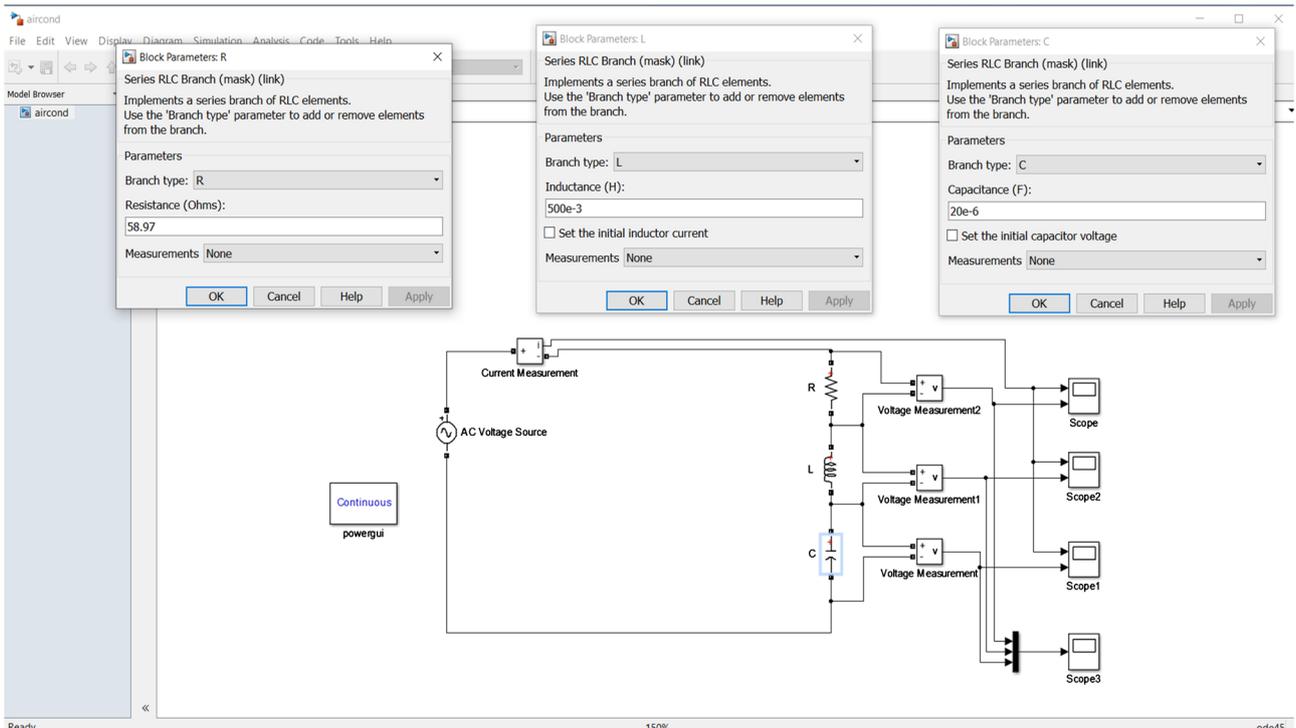


Figure 14. Simulink for air-condition.

$$\text{Inductive reactance, } X_L = 2\pi fL = 2\pi(50)(500 \times 10^{-3}) = 157.08 \Omega.$$

$$\text{Capacitive reactance, } X_C = \frac{1}{2\pi fC} = \frac{1}{2\pi(50)(20 \times 10^{-6})} = 159.15 \Omega.$$

$$\text{Circuit Impedance, } Z = \sqrt{R^2 + (X_L - X_C)^2} = \sqrt{58.97^2 + (157.08 - 159.15)^2} = 59.01 \Omega.$$

$$\text{Circuit Current, } I = \frac{v_s}{Z} = \frac{230}{59.01} = 3.9 \text{ A.}$$

Voltage across the series RLC circuit:

$$V_R = IR = 3.9 \times 58.97 = 229.98 \text{ V}$$

$$V_L = I(X_L) = 3.9 \times 157.08 = 612.61 \text{ V}$$

$$V_C = I(X_C) = 3.9 \times 159.15 = 620.69 \text{ V}$$

$$\text{Circuit factor, } \cos \theta = \frac{R}{Z} = \frac{58.97}{59.01} = 1A.$$

Phase angle, $\theta = 0.0368^\circ$.

5. Conclusions

The energy-saving circuit has been designed by using *Simscape* tools in MATLAB Simulink software. The simulation result for the inverter having 216 V DC as the input has been acquired for implementing the parameter of the control structure consisting of the cascade system which is calculated manually by using the formula. PR controller is used in the final design of the energy-saving circuit due to capability of the controller to have zero steady-state error. After combining the rectifier and inverter circuit, the gain of the controller will change, this may be due to the inconsistency of the rectifier output. This paper, demonstrates the concept of power saving by reducing the value of the voltage by implementing the energy-saving circuit which consisting of a single-phase thyristor rectifier, single-phase IGBT inverter of unipolar PWM generator, LC filter and PR controller. The energy saving circuit is automatically operated when the load is high at home, so that the voltage will reduce from 240 to other values up to 185 V, depends on the power used and the level of energy consumption.

In completing this work, several limitations are encountered. The circuit is designed by using MATLAB Simulink software. This software is complex which requires a prior knowledge in order to design the circuit in a short time. There is a lot of electric component and mathematical tool can be used in the MATLAB which make it harder to choose the right component for the circuit design. It takes a long time to understand the software due to the lack of familiarization towards the tools provided in it.

Concerning future works relevant to this research paper, there are several suggestions had been identified in order to improve the design? Firstly, since the type of the rectifier used in the circuit is full-bridge thyristor, a controller can be designed for this circuit in order to control the output of the rectifier. The value of the gain is expected to be the same as the value used for the inverter circuit. The change of the gain value for the entire circuit is not required.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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