

ORIGINAL RESEARCH

MODEL REFERENCE ADAPTIVE CONTROL FOR SINGLE PHASE BUCK BOOST INVERTER

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Abstract

An inverter is a device that converts DC voltage into AC voltage. AC output voltage is usually expected to be fixed and symmetrical at certain amplitudes and frequencies. Most inverters use a pulse width modulation circuit to regulate the output voltage. There are many topologies in building inverter circuits. In this research, the Buck-Bost topology is used to meet the output voltage greater or smaller than the input voltage. In this research, a Buck-Boost inverter is designed to convert a 12 volts DC input voltage to a 220 volts AC output voltage. In addition to the magnitude, the output voltage must also be considered of quality, in the sense that if there is a ripple, it should be as small as possible. For this purposed MRAC control is used, and simulated using Matlab. The test results with simulation show that the response of the SPBBI system with the MRAC controller with the MIT rule method can achieve the expected output voltage of 220V at the reference frequency of 49.95 Hz, 50 Hz, 50.05 Hz, and 60 Hz. System response is very dependent on the value of the adaptation gain. The adaptation gain that produces the best system response is 0.000001 with a settling time of 0.095 seconds.

KEYWORDS:

Adaptation Gain, Model Reference Adaptive Control, Pulse Width Modulation, Single Phase Buck-Boost Inverter

1 | INTRODUCTION

Electricity can be generated using a variety of energy sources in accordance with the geographical conditions of the region. Some use natural energy such as water, wind, sunlight, and geothermal^[1]. If none of that is available, another alternative is to use fuel oil or nuclear power as the last alternative^[2]. In addition to geographical conditions, what needs to be considered is the ease and cost of development. As a country located on the equator, it is very abundant in solar energy, so it is very appropriate to make electricity generation using solar panels^[3]. The problem is how when there is no sunlight. One solution is to add batteries as energy storage, which can be used without sunlight^[4, 5]. Because electricity used in industry and households is AC.

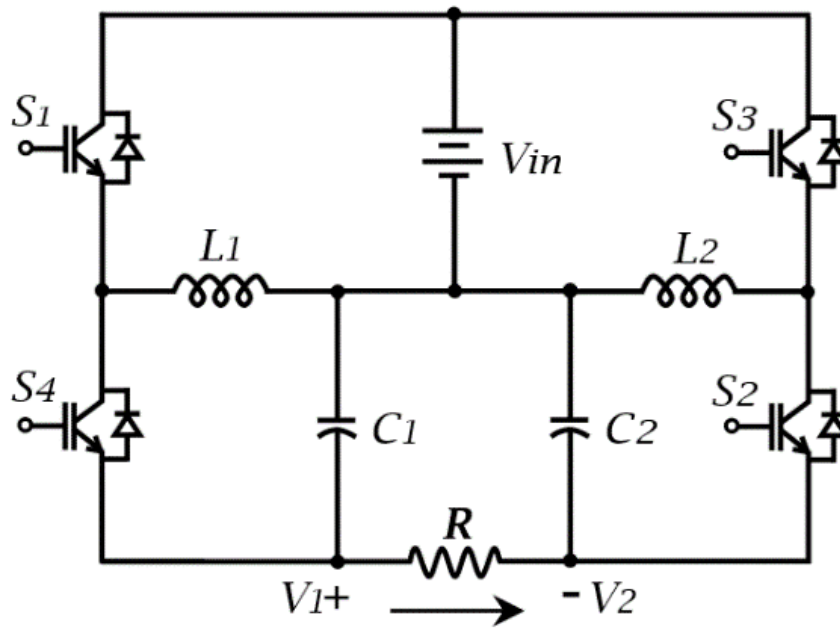


FIGURE 1 The single phase BuckBoost Inverter topology.

In contrast, the electricity stored in batteries is DC, while a device is needed to convert DC electricity into AC electricity, namely an inverter^[6].

Judging from the comparison of the output to input, there are three inverter topologies, namely buck (weaken), boost (strengthen), and buck-boost (can dilute or enhance, as needed)^[7-9]. Many inverter topologies have been developed to produce good output with low operating costs. This research used a single-phase buck-boost inverter topology (SPBBI)^[10]. The buck-boost inverter topology is compatible with the ever-changing power requirements, but the weakness is often found in chattering conditions on the output voltage signal. To regulate the output voltage and not the emergence of chattering, this research uses the Model Reference Adaptive Control (MRAC) method, which has a controller where the parameters can be adjusted (adjustable parameters) and has a mechanism for regulating the parameters^[11, 12]. In this research, the SPBBI output voltage is set at 220 volts in the form of a sinusoidal curve. The MRAC control system is expected to always keep the output voltage steady at 220 volts, despite changes in the load or changes in the input voltage by adjusting the SPBBI input reference signal.

2 | MATERIAL AND METHOD

2.1 | SPBBI Topology

One researcher who proposed a four-switch single-phase buck-boost inverter is Cáceres and Barbi^[6]. The open-close algorithm for the four switches is regulated by Sinusoidal Pulse Width Modulation (SPWM). On the first arm, when switch S1 opens, the S4 switch must close. Likewise, on the second arm, when switch S3 is open, then switch S2 must be closed. Switch S1 on the first arm is paired with switch S2 on the second arm when closed, then switch S4 on the first arm and switch S3 on the second arm will be in open condition, and vice versa will continue to alternate. The condition of opening and closing a switch in one arm may not overlap because it will cause a short circuit.

Based on Figure 1, we get the state space of the circuit when S1 and S2 are "ON."

$$\begin{bmatrix} \frac{dI_{Lb}}{dt} \\ \frac{dV_{Lb}}{dt} \end{bmatrix} = \begin{bmatrix} \frac{R}{Lb} & 0 \\ -\frac{1}{Cb} & \frac{1}{RCb} \end{bmatrix} \begin{bmatrix} I_{Lb} \\ V_{Cb} \end{bmatrix} \begin{bmatrix} \frac{R}{Lb} & \frac{1}{Lb} \\ 0 & \frac{1}{RCb} \end{bmatrix} \begin{bmatrix} I_{Cb} \\ V_{Ca} \end{bmatrix} \quad (1)$$

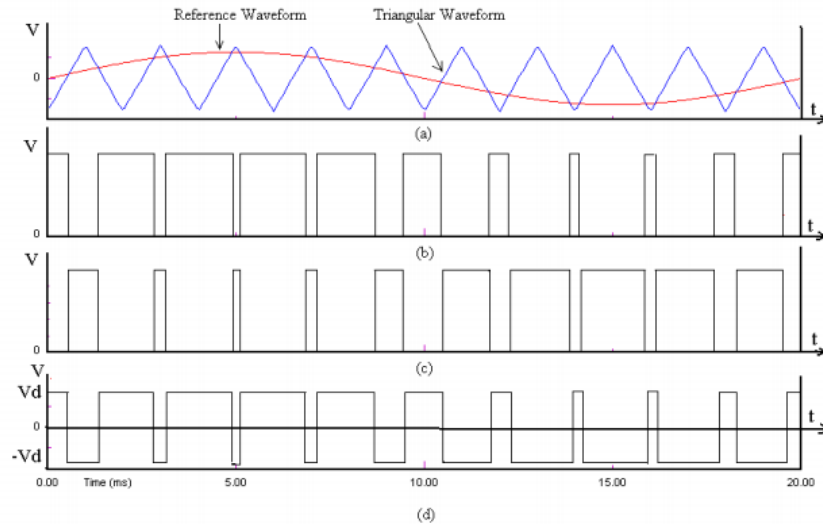


FIGURE 2 The SPWM with bipolar voltage switching.

Conversely, if S3 and S4 are "ON," the following state-space matrix will be obtained.

$$\begin{bmatrix} \frac{dI_{La}}{dt} \\ \frac{dV_{Ca}}{dt} \end{bmatrix} = \begin{bmatrix} \frac{R}{La} & 0 \\ -\frac{1}{Ca} & \frac{1}{RCa} \end{bmatrix} \begin{bmatrix} I_{La} \\ V_{Ca} \end{bmatrix} \begin{bmatrix} \frac{R}{La} & \frac{1}{La} \\ 0 & \frac{1}{RCa} \end{bmatrix} \begin{bmatrix} I_{Ca} \\ V_{Cb} \end{bmatrix} \quad (2)$$

2.2 | SPWM with Bipolar Switching

SPWM is a modulation technique that compares the sinusoidal wave as a reference signal and the triangular wave as a carrier signal to obtain the PWM signal used in the switching process. The carrier wave frequency determines the inverter switching frequency, while the reference wave frequency determines the inverter output frequency^[13, 14]. The output frequency is generated due to the comparison of the carrier waveform and the reference waveform, as shown in Figure 2. The modulation index can control the fundamental frequency component of the output voltage.

2.3 | SPWM with Bipolar Switching

A lowpass filter (LPF) is a filter that only passes frequencies lower than the cut-off frequency (f_c) and will weaken the signal with a frequency higher than the cut-off frequency (f_c). The cut-off frequency point is 0.707 or -3dB ($\text{dB} = -20 \text{Log } V_{\text{out}} / V_{\text{in}}$) of the voltage gain allowed to pass. The LPF RLC passive filter circuit is described as a second-order circuit. A second-order differential equation can describe any voltage or current in the circuit in the circuit analysis.

$$H(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \quad (3)$$

With ω_n as a natural frequency and ζ as a damping ratio of the system. The value of both can be determined with

$$\omega_n = 2\pi f_c \quad (4)$$

$$\zeta = \frac{1}{2Q} \quad (5)$$

Where f_c is the cut-off frequency and Q is the quality factor. The quality factor value for LPF is 0.707.

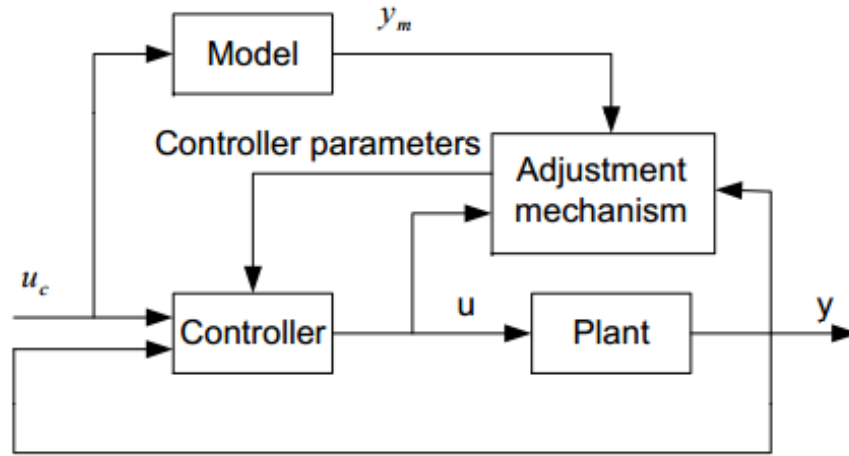


FIGURE 3 Basic principles of Model Reference Adaptive Control (MRAC) systems .

2.4 | Model Reference Adaptive Control (MRAC) System

The adaptive control system is a control system where the parameters can be set and also has a mechanism to regulate these parameters^[11, 12, 15]. Model Reference Adaptive Control (MRAC) is one of the adaptive control schemes where the system output (process) performance follows the reference model's output performance. The controller parameters are regulated through an adjustment mechanism based on an error which is the difference between the process output and the reference model output. The block diagram of the MRAC scheme is shown in Figure 3 .

The MRAC system scheme has two loops, the first is the loop that feedbacks between the process and the controller (inner loop), and the second is the loop that changes controller parameters based on the error signal $e = y - y_m$ (outer loop). Control is done by minimizing the error signal so that the system output (y) matches the output of the reference model (y_m). SPBBI is a reference model that is used as a reference to produce a specified output voltage of 220 V. The transfer function is obtained from Eq. 1 and Eq. 2, i.e.

$$G(s) = \frac{\frac{R}{L}s - \frac{1}{CL}}{s^2 + \left(\frac{-R}{L} + \frac{1}{CL}\right)s + \frac{1}{CL}} \quad (6)$$

where $a = \frac{1}{CL}$ and $b = \frac{R}{L}$ can be simplified

$$G(s) = \frac{bs - a}{s^2 + (-b + a)s + a} \quad (7)$$

The second-order transfer function of the MRAC reference model based on the mathematical model of the SPBBI system is

$$G(s) = \frac{b_m s - a_m}{s^2 + (-b_m + a_m)s + a_m} \quad (8)$$

MIT Rule in a closed-loop system where the controller has an adjustable parameter that is the adaptation parameter θ . The closed-loop system response is determined by the model whose output is notated y_m . The process output is denoted as y . The error indicated e is the difference between the output y of the closed-loop system and the output of the y_m model. Parameter settings are performed by minimizing the loss function (The loss function, $J(\theta)$).

$$J(\theta) = \frac{1}{2e^2} \quad (9)$$

For J to have a small value, a parameter change is made on the negative gradient of J .

$$\frac{d\theta}{dt} = -\gamma \frac{\partial J}{\partial \theta} = -\gamma e \frac{\partial e}{\partial \theta} \quad (10)$$

The equation is called the MIT rule, where the partial derivative $\frac{\partial e}{\partial \theta}$ is called a system sensitivity derivative that shows how errors are affected by adjustable parameters. Updating controller parameters can be modeled,

$$u(k) = k_1 u_c(k) - k_2 y(k) \quad (11)$$

If k_1 and k_2 satisfy the equation

$$k_1 = \frac{b_m s - a_m}{b s - a} \quad (12)$$

$$k_2 = \frac{(-b_m + a_m)s + a_m - (-b + a)s - a}{b s - a} \quad (13)$$

$u(k)$ is the control signal, k_1 and k_2 are parameter updates, u_c is the input reference and y is the plant output. Error is the difference between SPBBI output (y) and reference SPBBI output (y_m)

$$e = y - y_m \quad (14)$$

$$e = G(s) u(k) - G_m(s) u_c \quad (15)$$

$$y = \frac{b s - a}{s^2 + (-b + a)s + a} (k_1 u_c - k_2 y)$$

$$y = \frac{(b s - a)k_1}{s^2 + (-b + a)s + a + (b s - a)k_2} u_c \quad (16)$$

by substituting Eq. 16 to Eq. 15, we could obtain

$$e = \frac{(b s - a)k_1}{s^2 + (-b + a)s + a + (b s - a)k_2} u_c - G_m(s) u_c \quad (17)$$

Sensitivity derivatives are obtained by performing partial derivatives in errors of the parameters k_1 and k_2 .

$$\frac{\partial e}{\partial k_1} = \frac{(b s - a)k_1}{s^2 + (-b + a)s + a + (b s - a)k_2} u_c \quad (18)$$

$$\frac{\partial e}{\partial k_2} = \frac{(b s - a)^2 k_1}{(s^2 + (-b + a)s + a + (b s - a)k_2)^2} u_c$$

$$\frac{\partial e}{\partial k_2} = \frac{(b s - a)}{s^2 + (-b + a)s + a + (b s - a)k_2} y \quad (19)$$

Values a and b are constant values of the system. In the MRAC design it is assumed that the characteristics or values of the system are unknown, therefore an approach or estimate based on that is needed

$$s^2 + (-b + a)s + a + (b s - a)k_2 \approx s^2 + (-b_m + a_m)s + a_m$$

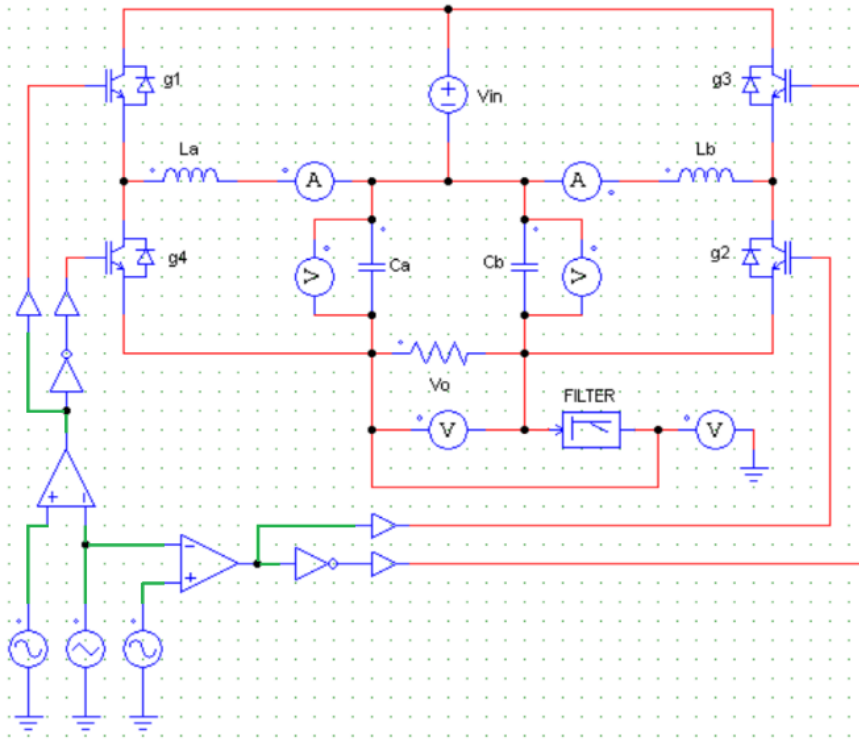


FIGURE 4 SPBBI circuits on PSIM.

which will be achieved when the right parameters are at the right price^[12]. With Eq. 19 and this approach, the control parameter is updated.

$$\frac{dk_1}{dt} = -\gamma \left(\frac{bs - a}{s^2 + (-b + a)s + a + (bs - a)k_2} u_c \right) e \quad (20)$$

$$\frac{dk_2}{dt} = \gamma \left(\frac{bs - a}{s^2 + (-b + a)s + a + (bs - a)k_2} y \right) e \quad (21)$$

Where γ is the adaptation gain, the control signal is determined based on Eq. 11, i.e.

$$u(k) = \left[-\gamma \left(\int \frac{bs - a}{s^2 + (-b + a)s + a + (bs - a)k_2} u_c \right) e \right] u_c - \left[\gamma \left(\int \frac{bs - a}{s^2 + (-b + a)s + a + (bs - a)k_2} y \right) e \right] y \quad (22)$$

2.5 | Design of the SPBBI System

This research carried out SPBBI design using PSIM and Matlab software. SPBBI input is a 12 volt DC voltage to be changed to a maximum AC voltage of 220 volts at a certain frequency by changing the duty cycle. In the power simulator (PSIM), the circuit is depicted in Figure 4. The output voltage is adjusted by changing the value of the duty cycle. Filters installed at the end of the circuit are used to remove ripple at the output voltage.

Besides being simulated using PSIM, the SPBBI design was also simulated using Matlab software. SPBBI voltage control block diagram with the MRAC method in the Matlab software simulation is shown in Figure 5. The u is a control signal The UC is an input reference. The d is the switching signal 0,1. The y is output from SPBBI. The y_m is the output from the SPBBI reference. Table 1 shows the SPBBI parameters and their values.

State space equation when S1 and S2 are "ON" to be

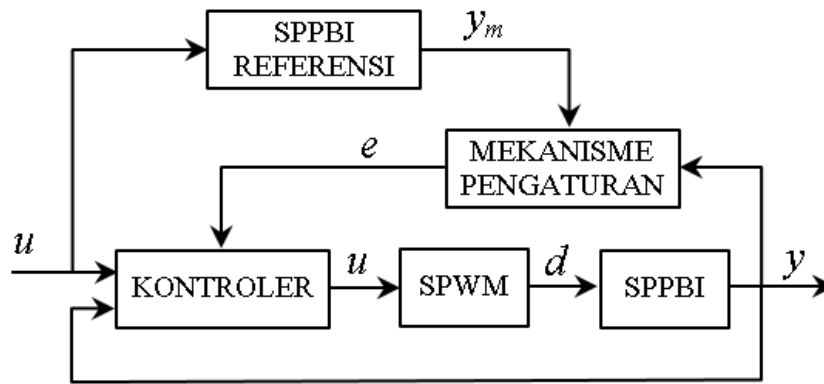


FIGURE 5 SPBBI block diagram with MRAC control.

TABLE 1 SPBBI parameters.

Parameter	Value
R	65
La=Lb	360 H
Ca= Cb	22 F
f carrier	2000 Hz
f reference	50±0.05Hz and 60 Hz
Fc (cut off frequency)	50±0.05Hz and 60 Hz
Vin	12 V

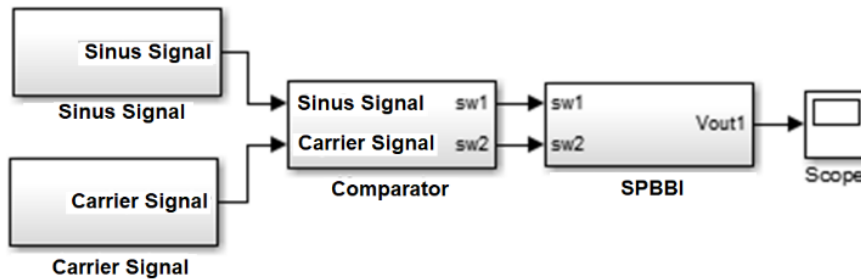


FIGURE 6 Simulation block diagram of SPBBI without controller.

$$\begin{bmatrix} \frac{dI_{Lb}}{dt} \\ \frac{dV_{Lb}}{dt} \end{bmatrix} = \begin{bmatrix} \frac{65}{0.00036} & 0 \\ -1 & \frac{1}{0.00143} \end{bmatrix} \begin{bmatrix} I_{Lb} \\ V_{Cb} \end{bmatrix} \begin{bmatrix} \frac{65}{0.00036} & \frac{1}{0.00036} \\ 0 & \frac{1}{0.00143} \end{bmatrix} \begin{bmatrix} I_{Cb} \\ V_{Ca} \end{bmatrix}$$

State space equation when S3 and S4 are "ON" to be

$$\begin{bmatrix} \frac{dI_{La}}{dt} \\ \frac{dV_{La}}{dt} \end{bmatrix} = \begin{bmatrix} \frac{65}{0.00036} & 0 \\ -1 & \frac{1}{0.00143} \end{bmatrix} \begin{bmatrix} I_{La} \\ V_{Ca} \end{bmatrix} \begin{bmatrix} \frac{65}{0.00036} & \frac{1}{0.00036} \\ 0 & \frac{1}{0.00143} \end{bmatrix} \begin{bmatrix} I_{Ca} \\ V_{Cb} \end{bmatrix}$$

Based on SPBBI modeling in the state space equation in equations (1) and (2), then it is simulated into the Matlab software shown in Figure 6 .

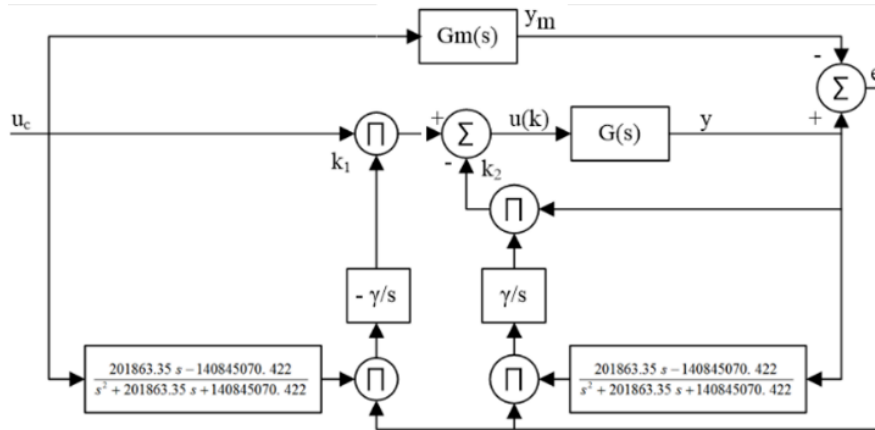


FIGURE 7 SPBBI with MRAC control system.

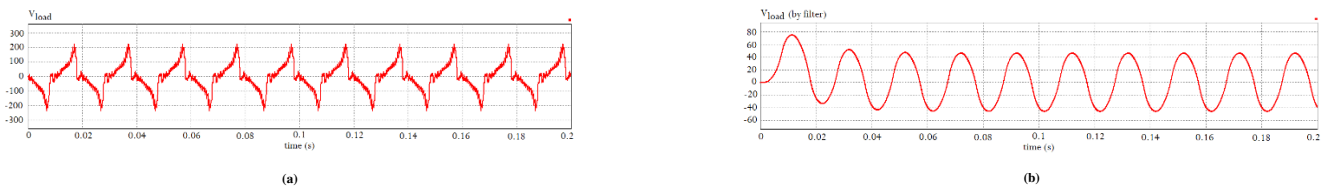


FIGURE 8 The output voltage curve at load, (a) without a filter and (b) with a filter

Using the transfer function as a mathematical model of the MRAC control system and a mathematical model of the control system changes, it is simulated in the Matlab software with the gain and control gain values varying between 0.000001 to 0.1.

The control signal is determined based on Eq. 22,

$$u(k) = \left[-\gamma \left(\int \frac{201863.35s - 140845070.422}{s^2 + 201863.35s + 140845070.422} u_c \right) e \right] u_c - \left[\gamma \left(\int \frac{201863.35s - 140845070.422}{s^2 + (-b + a)201863.35s + 140845070.422} y \right) e \right] y$$

Figure 7 shows that the error is the difference between the output of the reference model (y_m) and the process output (y). The k_2 controller parameter update is obtained as a result of the multiplication between error (e), adaptation gain (γ), and process output (y) after going through the product with a reference model. In contrast, the k_1 parameter update is obtained due to the multiplication between error (e), adaptation gain, and reference input (u_c) after passing the product with a reference model.

2.6 | Result Analysis

2.7 | SPBBI Analysis on PSIM Software

System analysis starts by simulating the circuit topology in Figure 4 into the PSIM simulator software by entering the SPBBI parameter values in Table 1. The circuit's output voltage is shown in Figures 8 a and Figure 8 b. Figure 8 is the output voltage without being filtered, while Figure 8b is the output voltage using a filter.

Initially, the inductor and capacitor are still empty, so the output voltage appears to be unstable between 0 to 0.11 seconds, as shown in Figure 8 b. After 0.11 seconds, the output voltage has stabilized. This happens because initially, inductor L_a is empty or uncharged. The source voltage fills the two inductors alternately based on a regulated switching pattern. Instability at the beginning of charging the inductor results in instability of charging at the capacitor. The charge on the capacitor is obtained from the inductor through the resonant effect. When the source fills the charge at the inductor L_a , the resonance effect between the inductor and the capacitor causes the charge at the inductor L_b to flow to capacitor b and vice versa when the source fills the inductor L_b . Charge on the two inductors arranged according to the scaling pattern causes a continuous load buildup on the

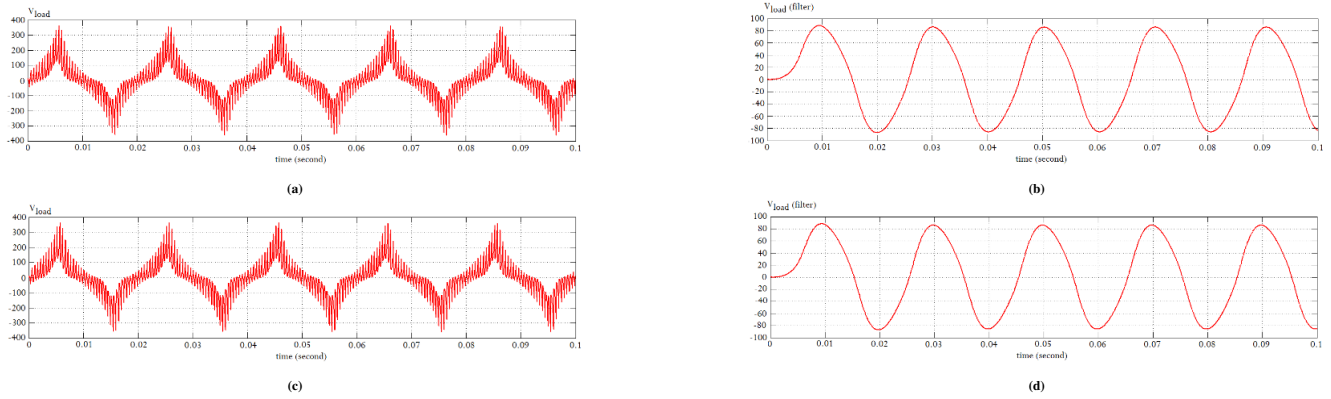


FIGURE 9 Output voltage curve with a reference frequency of 50 ± 0.5 Hz. (a) reference frequency 49.5 Hz without filter (b) reference frequency 49.5 Hz with filter (c) reference frequency 50.5 Hz without filter (d) reference frequency 50.5 Hz with filter.

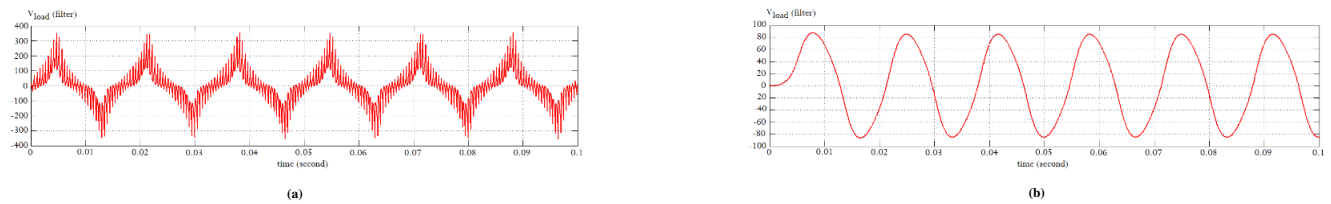


FIGURE 10 Output voltage curve at 60 Hz reference frequency. (a) without filter (b) with filters

two inductors. This is because not all the L_b inductor charges flow to the capacitor C_b . There has been a continuously changing of time "ON" and vice versa. So that the buildup and storage of these charges make the input voltage of 12 V can be increased up to 220 V

2.8 | SPBBI Analysis on Matlab Software

SPBBI is expected to operate at the reference frequency set by PLN with a tolerance of ± 0.5 Hz. The SPBBI state-space model in equations (1) and (2) are simulated using the Matlab program by entering the parameter values in table 1. The output voltage, which is the potential difference between the capacitor C_b and the C_a capacitor, is 365 V. There are still many ripples, so a filter is needed. The filter installed in this system is a second-order lowpass filter. The SPBBI output voltage with a reference frequency of 49.5 Hz without the filter is shown in Figure 9 a, 370 volts. The output voltage is not as expected because it still contains a lot of noise or ripple, so we need the appropriate filter.

After filtering, noise at the output voltage can be removed, and the curve becomes sinusoidal as expected. The effect is that the maximum output voltage is only 89 volts, as shown in 9 (b). In Figure 9 c, the SPBBI output voltage is shown unfiltered at a reference frequency of 50.5 Hz, 363 volts. The output voltage is 87 volts when a filter is used, as shown in Figure 9 d.

At the 60 Hz reference frequency, the SPBBI output voltage is lower than the 50 Hz reference frequency, which is 355 volts, as shown in Figure 10 a. Likewise, when a filter is added to the circuit, for a reference frequency of 60 Hz, the output voltage is 86 volts. This is due to the difference in the pattern of scaling formed when the reference frequency is 50 Hz and 60 Hz

Figure 11 shows the switching pattern at SPWM with a reference frequency of 50 Hz (Figure 11 a) and at a reference frequency of 60 Hz (Figure 11 b). The difference between the two patterns is in the pulse width when On and Off. At the reference frequency, 50 Hz has a pulse width more than the 60 Hz one, so charging more capacitors on the charge.

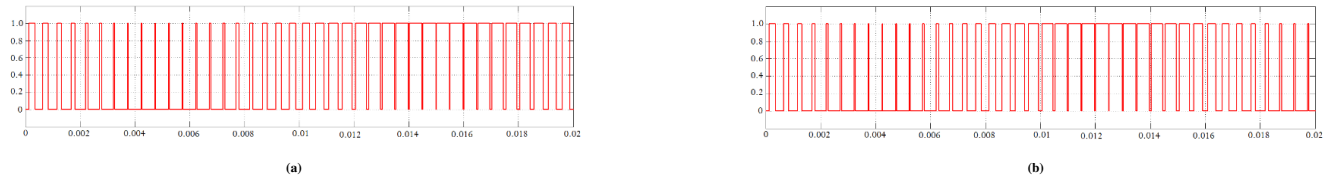


FIGURE 11 Switching patterns on switches: (a) SPWM with a reference frequency of 50Hz (b) SPWM with a reference frequency of 60Hz

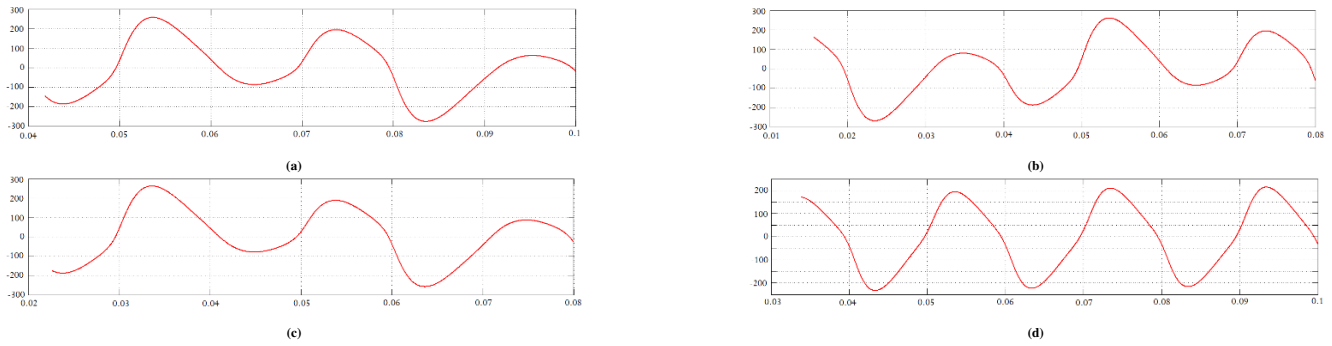


FIGURE 12 MRAC system response with 0.00001 adaptation gain at the reference frequency: (a) 49.95 Hz (b) 50 Hz (c) 50.05 Hz (d) 60Hz.

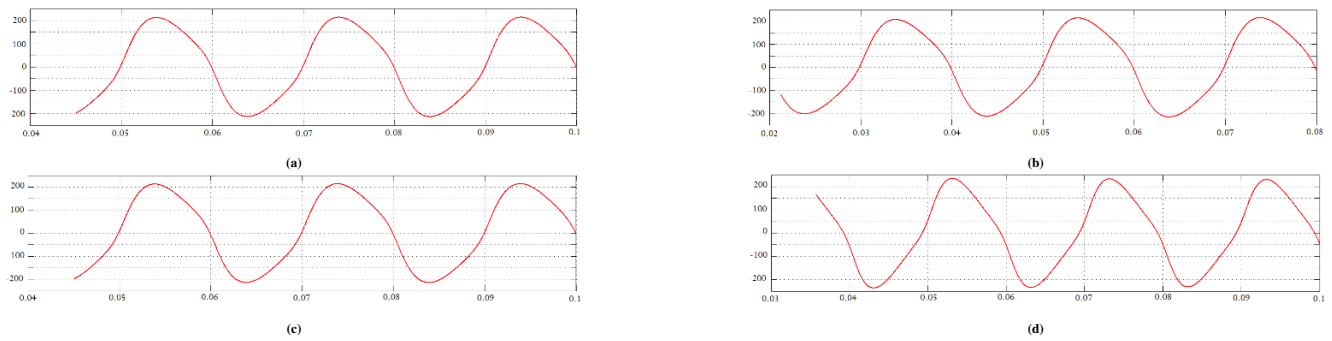


FIGURE 13 MRAC system response with 0.000001 adaptation gain at the reference frequency: (a) 49.95 Hz (b) 50 Hz (c) 50.05 Hz (d) 60Hz.

2.9 | Analysis of MRAC for SPBBI

MRAC performance testing as an SPBBI controller is performed for adaptation gain values between 0.000001 to 0.1. This test was conducted to determine the effect of adaptation gain on SPBBI output. The test is carried out at several reference frequencies to obtain the system response curve, namely at 49.5 Hz, 50.0 Hz, 50.5 Hz, and 60 Hz. The MRAC system response curves shown for the four reference frequencies are only for the adaptation gain of 0.00001 and 0.000001, as shown in Figures 12 and Figure 13. The system response curve of the test results in Figure 12 and Figure 13 shows the system’s performance.

The system response in following the reference model is strongly influenced by the magnitude of the adaptation gain value. Different adaptation gain values will result in different system responses following the reference model. The smaller the gain value, the closer the desired output voltage value. This is caused by the results of the control signal from the MRAC control. The higher the gain value, the value of the output voltage on the control signal is also higher and vice versa. This control signal will affect the width of the narrow signal reference or can affect the duty cycle. At the adaptation gain of 0.1 - 0.0001, the system response produces an unstable curve and has not formed a sine signal. This is caused by control signals that are not stable and

tend to decrease so that it will affect the output of the reference signal that has been controlled. In Figure 12 -a, -b, and -c, the resulting response curve is not yet stable but has formed a sine signal. The control signal generated is also not stable but has formed a sine signal.

In Figure 12 d, the SPBBI response curve with a frequency of 60 Hz shows that the gain of an adaptation of 0.00001 the b and c, the SPBBI response curve at frequencies 49.95Hz, 50Hz, and 50.05Hz has reached the desired output voltage of 220 V. In Figure 13 d it is shown that the SPBBI response curve with a frequency of 60 Hz which produces an output voltage of 235 V. The test results show that the response of the SPBBI system with the adaptive MRAC controller MIT method can achieve the expected output voltage of 220V at the reference frequency of 49.95 Hz, 50 Hz, 50.05 Hz, and 60 Hz. The test results are shown when the system characteristics change. The system can adapt to the mechanism of setting the control parameters, namely the adaptation gain.

3 | CONCLUSION

A successful simulation of the application of the MRAC control system has been carried out as an SPBBI output voltage controller. The test results with simulation show that the response of the SPBBI system with the MRAC controller with the MIT rule method can achieve the expected output voltage of 220V at the reference frequency of 49.95 Hz, 50 Hz, 50.05 Hz, and 60 Hz. System response is very dependent on the value of the adaptation gain. The adaptation gain that produces the best system response is 0.000001

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CREDIT

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