Topology and Performance of DC Multi Converter for Multi Mini Hydro-Generator

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Abstract—**Energy wasted in the household streams can be easily found in the water faucets, showers, toilet sprinkles, and other equipment in plumbing systems where water only flows to clean out before it becomes a waste substance. Energy from flowing waters can be collected and converted to more useful forms of energy like electricity as it can be immediately utilized or stored. In the further development of the mini compact turbine generator (MCTG), the water flowing through every part of the house plumbing system is intended to be collected as electrical power. Unfortunately, the voltage produced by the conventional MCTG is insufficient for immediate applications in various electrical devices. In addition, the generated voltage does not conform to the voltage rating of the battery's terminal as a medium for storing electrical energy. This research proposes the performance improvement of the MCTG output to produce a higher voltage by adding a DC boost converter, which can operate in a single or cascaded configuration to address issues with the MCTG output voltage and the boost converter's efficiency when operating in high duty cycle values. Designs and simulations were conducted to obtain the expected criteria for electrical voltage generation. Several topologies tested included the single converter system, cascaded converter system, cascaded converter system with a selector, and parallel system. The results demonstrated that the parallel system worked better than the three topologies as it could yield voltage according to the reference voltage of 14 V and efficiency above 0.9 on the broader range of rotations of the MCTG rotor shaft.**

Keywords—**Cascaded Voltage Boost Converter, Efficiency, Harvesting Energy from Surrounding Houses, Pico Hydro, Wasted Energy Converter.**

I. Introduction

Numerous energy sources in the surrounding environment can be utilized to generate electricity; this practice is widely known as harvesting energy from surrounding houses. By using surrounding energy, a power generation system can be built to supply household needs. Energy sources that can be utilized include water, wind, solar, and other renewable energies. Generated electrical energy is then processed using a converter before being distributed to the load [1]. When operating the converter, the duty cycle is required to be limited so that the converter performance is maximum, especially the boost converter, which tends to have a lower efficiency when operated in the higher duty cycle value [2], [3].

Fossil energy sources power most power plants in Indonesia; only 10.9% of the 70.96 GW of energy generation utilizes renewable energy sources, implying that 89.1% or around 63.23 GW of energy generation comes from fossil fuels [4], [5]. Besides harming natural sustainability, massive and continuous exploitation of fossil energy sources can cause pollution produced by electrical generation units utilizing that fossil energy. The construction of power plants with portable renewable energy sources can also be considered for ease of use [6]. One of the renewable energy sources used as an alternative energy source is hydropower. Approximately 75,000 MW of electrical energy could be generated through the use of hydropower as an energy source. Of this tremendous potential energy, only 2.5% has been utilized. As much as 10% of the total potential energy, or 7,500 MW, can be used for micro hydropower plants (*pembangkit listrik tenaga mikrohidro*, PLTMH) [7]. Unfortunately, the hydroelectric power plants (*pembangkit listrik tenaga air*, PLTA) with massive capacity and size can only be constructed in specific locations, not to mention its challenging distribution to reach remote areas. Moreover, the construction of PLTA with massive capacity and size necessitates a big dam. This construction might disrupt the river ecosystem where the PLTA is built because the dam can cut off the path between the upper and lower rivers so as to isolate animals [8]. One of the solutions to address this issue is by building PLTMH or even a smaller power plant with power under 5 kW called pico hydropower plants (*pembangkit listrik tenaga pikohidro*, PLTPH) [9]. PLTMH and/or PLTPH can be used to generate electricity in areas with limited water energy sources [8]. The construction of power plants using renewable energy sources in parallel with similar generators and/or in hybrid (combination with other energy sources) can be a solution for the little amount of electricity produced by a single generator [10], [11].

Around or even inside the house, flowing water can be found in the water faucets, showers, and other equipment in the plumbing systems. Energy from flowing water is frequently wasted in the drainage after being used for daily needs such as washing hands. In fact, the energy found in the flowing water in pipes can be utilized as a source to generate electrical energy. Much research on the utilization of wasted energy existing in the water flowing through pipes has been conducted, two of which are on the water transmission pipeline in United Arab Emirates [12] and on the sewage pipes [13]. This research analyzes the use of several converters by adjusting the connection between converters in the systems using a number

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of generators so as to gain higher and more stable efficiency at a wider range of the generator's rotor shaft rotation. The use of several converters operated in a single or cascaded configuration following the condition is expected to resolve the efficiency issue in the boost converter when operated in the higher duty cycle value [2], [3]. The duty cycle is the high-state duration of the trigger signal divided by the period of the trigger signal. The trigger signal is used to trigger the transistor gate in the converter. The results of this study are expected to play a role in optimizing electrical energy systems; meeting the needs of electrical energy in hard-to-reach areas or areas where the grid network installments are still difficult to realize; or increasing the independence of obtaining energy in society.

II. Utilization of Wasted Energy in Water Flow in Household Plumbing Systems

The utilization of the wasted energy in the water flow as a source to generate electrical energy has been previously studied in which some have studied the water flow in pipes [12]-[16]. In [12], the transmission water pipelines produced a generation potential of 5.7 MW/year. However, in this research, the electricity generated was not processed using power electronic devices [12]. Other research has utilized wasted energy from wastewater flow in distribution pipes [13]. By installing an overhead storage tank with a height of 14 m and adjusting the water flow to 9 ℓ/s, the generator could produce electrical power up to 212 W. Nevertheless, no power electronic devices were used in this research to process the generated electricity. Research on water pipes sized 100 mm has also been conducted [14]. By setting the water discharge to 1.5 m/s and the head loss to less than 5 m, the generator could produce generated power up to 88.2 W. Then, using the water pipes of 100 mm and setting a head loss to under 5 m, it was obtained power of 200 W, and the turbine as well as generator efficiency up to 33% [15]. Unfortunately, the water discharge was not reported in this study. In addition, power electronic devices were not employed to process generated electricity [14], [15]. Research on water flow through pipes in a university building has also been carried out [16]. By using a 3D printed turbine, the turbine efficiency obtained was 40%, with a potential power in the water flow of 91 W. However, this study did not use turbine-connected generators or power electronic devices.

Utilization of water flow closer to our surroundings can also be done by using converters and/or other power electronics devices; the output voltage from the generator can be processed first before being distributed to the load [1]. The buck-type converter can be used to lower the voltage, the boost-type converter can be used to increase the voltage, and the buck-boost converter can be used to decrease and increase the voltage [17]. The operation of the boost converter tends to result in lower efficiency as the duty cycle increases. After the duty cycle exceeds the critical duty cycle value, the efficiency of the boost-type converter will fluctuate, with the lowest value being lower than when the duty cycle value has not reached the critical duty cycle value [3]. Limiting the value of the duty cycle on the operation of the boost-type converter is required for the converter to work optimally [2]. The efficiency characteristics of this boost-type converter become the consideration, whether the converter will be operated in a single or cascaded configuration.

A. *Utilization of Energy Sources Around the House*

Water is one of nature's most abundant sources of energy. Water undergoes a constant cycle so that its availability is maintained. Water can also be found in the plumbing system at home and is used for daily needs. The generation of electrical energy from energy sources around the houses can be termed as harvesting energy from surrounding houses [1].

B. *Generator*

Water can be obtained from various sources, one of which is the water flow in pipes. Household piping systems generally use a ½ in pipe, so a generator that can be installed and in accordance with the size of the pipe is needed. The generator must be connected to a small turbine to match the pipe's size. The mini compact turbine generator (MCTG) is suitable for these conditions. The generator used can be a permanent magnet DC generator; since the permanent magnet generates the magnetic flux, the generator size can be more compact because there is no excitation circuit. However, due to the magnetic flux in permanent magnets being fixed and limited, these generators are generally suitable for low-power generation [18].

The selection of a generator is also inseparable from the load plan to be supplied, in the form of an accu. The charging voltage of the accu is about 13.8 V to 14 V, referring to the specifications of the accu charger [19] and the measurement of accu charging on motorcycles. Generators available on the market include an output voltage of 5 V, 12 V, and 80 V [20]. So that the voltage value conversion is not that big, a generator with a voltage of 12 V was selected. In several previous studies [12]-[16], [21], [22], the generator output voltage was not processed by power electronic devices. The maximum generator output voltage was 12 V, so a voltage boost converter was necessitated to obtain a voltage of 14 V.

C. *Converter*

There are several types of DC converters [17]. Since the desired function is to increase the generator's output current from 12 V to 14 V, the selected converter is the boost converter. The basic topology of the boost converter can be seen in Fig. 1. The fundamental topology component of the boost converter consists of an inductor (L), a diode (D), a switch which can be a transistor (Q), and a capacitor (C) as a filter. The converter can be connected to a DC source voltage (V_{in}) and a load (R).

The following equation is used to calculate the output voltage of the basic topology of the boost converter [17].

$$V_{out} = V_{in}\left(\frac{1}{1-D}\right) \quad (1)$$

with:

$D = \frac{t_{on}}{T}$

$T = t_{on} + t_{off}$

$t_{off} = (1-D)\,T.$

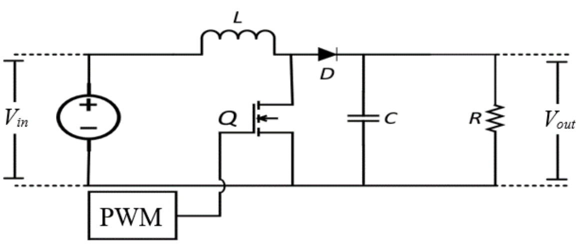

Fig. 1 Basic topology of the boost converter.

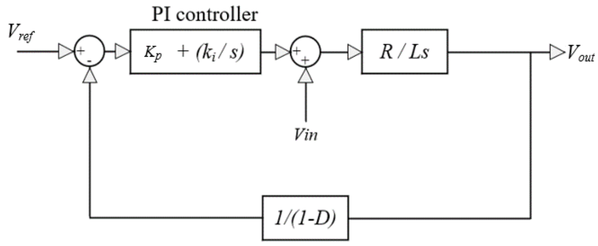

Fig. 2 Closed loop system of boost converter with PI controller [26].

V_{in} is the source voltage (input voltage), V_{out} is the voltage at the load (output voltage), t_{on} is the duration when pulse width modulation (PWM) signal is high, t_{off} is the duration when PWM signal is low, D is the duty cycle. T is the PWM signal period.

The following equation is used to calculate the minimum value of the inductor [23].

$$L_{min} = \frac{D_{min}(1-D_{min})^2\, R}{2f} \tag{2}$$

where L_{min} is the minimum value of the inductor, D_{min} is the minimum value of the duty cycle, R is the resistive load, and f is the operating frequency value of the converter.

The following equation is used to calculate the minimum value of the capacitor [23].

$$C_{min} = \frac{D_{max}}{R(\,\Delta V_{out}/\,V_{out})f} \tag{3}$$

where C_{min} is the minimum value of the capacitor, D_{max} the maximum value of the duty cycle, R is the resistive load, ΔV_{out} is ripple, and f is the operating frequency value of the converter.

D. Control and Converter Stability

The input voltage and the PWM signals of the duty cycle, which control the work of the converter switch, affect the converter's output voltage. A control method for the PWM signal generation is required to maintain the converter's optimum performance and obtain a more accurate output voltage. The most frequently used methods include proportional (P) control, proportional-integral control (PI), proportional-integral-derivative (PID) control, proportional-derivative (PD) control [24]. The PI control was selected since it is more commonly used to control processes with relatively fast dynamics (i.e., flow, pressure, and level) [25].

The closed loop system in the boost converter with PI control is illustrated in Fig. 2. In Fig. 2, there is a reference voltage (V_{ref}); a PI control that has a constant of proportionality components (k_p) and an integral constant (k_i); a resistive load component (R) and an inductor (L); a multiplier component of the boost converter (*1/(1 - D)*) where D denotes the duty cycle; the error signal (e); and the output voltage (V_{out}).

Based on Fig. 2, the transfer function of the boost converter is obtained as follows [26].

$$G = \frac{V_{out}}{V_{in}} = \frac{\frac{R}{Ls}}{\left[1+\left(\frac{R}{Ls}\right)\left(k_p+\frac{k_i}{s}\right)\left(\frac{1}{1-D}\right)\right]} \tag{4}$$

Based on this transfer function, PI control parameter values can be calculated and determined by taking into account the stability of the system. One of the stability concepts that can be understood is the Routh-Hurwitz stability concept [24].

To do calculations with the Routh-Hurwitz stability concept, the system's transfer function needs to be arranged in the form of a polynomial in Laplace.

$$a_0 s^n + a_1 s^{n-1} + \ldots\ldots + a_{n-1}s + a_n = 0 \tag{5}$$

where a_0 denotes constant on the Laplace number with the highest power s^n, and a_n denotes constant on the Laplace number with the lowest power s^0.

If there is a constant (a) of zero or negative, the polynomial has an imaginary root or a positive real part, meaning that the system is unstable. If all the coefficients are positive, they can be arranged into rows and columns according to the following pattern.

s^n	a_0	a_2	a_4	a_6	…	…
s^{n-1}	a_1	a_3	a_5	a_7	…	…
s^{n-2}	b_1	b_2	b_3	…	…	…
…	…	…	…			
…	…	…	…			
s^2	c_1	c_2				
s^1	d_1					
s^0	e_1					

where,

$$\begin{aligned} b_1 &= \frac{a_1a_2-a_0a_3}{a_1}\ ;\ b_2 = \frac{a_1a_4-a_0a_5}{a_1}\ ;\ b_3 = \frac{a_1a_6-a_0a_7}{a_1} \\ c_1 &= \frac{a_1a_2-a_0a_3}{a_1}\ ;\ c_2 = \frac{a_1a_4-a_0a_5}{a_1}\ ;\ c_3 = \frac{a_1a_6-a_0a_7}{a_1} \\ d_1 &= \frac{a_1a_2-a_0a_3}{a_1}\ ;\ d_2 = \frac{a_1a_4-a_0a_5}{a_1}\ ;\ d_3 = \frac{a_1a_6-a_0a_7}{a_1} \\ &\ldots\ ;\ \ldots\ ;\ \ldots \end{aligned} \tag{6}$$

Based on the Routh-Hurwitz stability concept, the system is considered stable when all constants in the first column (a_0, a_1, b_1, c_1, d_1, ...) are positive.

E. Efficiency

Generally, the efficiency on the single and cascaded devices is illustrated in Fig. 3. The efficiency of the single device can be expressed below.

$$\eta = \frac{P_{out}}{P_{in}} \tag{7}$$

with P_{in} denotes the input power, and P_{out} denotes the output power of the system.

On the other hand, the efficiency of the cascaded device can be expressed below.

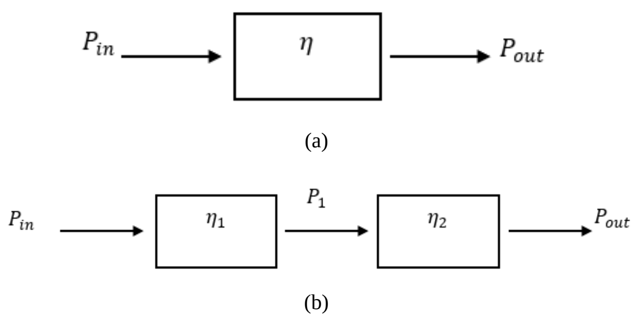

Fig. 3 Efficiency of (a) single device and (b) cascaded devices.

$$\eta_{total} = \frac{P_{out}}{P_{in}} = \frac{P_1\,\eta_2}{P_1/\eta_1} = \eta_1\eta_2 \quad (8)$$

with P_{in} denotes the input power and P_{out} denotes the output power of the system. In real conditions, the efficiency of a device is always less than one. Hence, theoretically, cascaded devices have lower total efficiency than single devices.

III. Methods

This research was conducted using the Powersim (PSIM) software. Nevertheless, measurement results in the initial experiment on the generator were carried out to assist in adjusting the generator parameters. This research is a continuation of the initial research which conducted the measurement of generator parameters and initial simulation of a single and cascaded converter system [27]. This paper discusses further performance, especially voltage and power efficiency in the single converter system, cascaded converter system, cascaded converter system with a selector, cascaded converter system with a trigger, control, and selector circuits.

A. Preliminary Investigation of System Components

The generator used as a reference was a permanent magnet generator with a maximum DC output voltage of 12 V, a power rating of 10 W, and an anchor resistance of 10.5 Ω [20]. An initial investigation of the generator was carried out by measuring the generator output voltage at no load and with a load of 60 Ω. The measurement data were then used as a reference to assist in determining the generator parameters in the simulation.

The measurement results obtained a maximum generator voltage of 10.232 V and a minimum generator voltage of 3.2 V. The converter was designed to work under continuous conduction mode (CCM) with a voltage ripple of less than 1%; hence, it was obtained the boost converter parameters as seen in Table I. If the switching frequency is too low, the output voltage ripple gets higher. However, it is important to understand that excessively high switching frequency increases the current consumption on the MOSFET (Q) switch used and causes the MOSFET temperature to be high [28].

B. Converter and Generator System Topology

The block diagram of the system is presented in Fig. 4. The switch (S) was used to select the system configuration, whether the converter in each system was operated in a single or

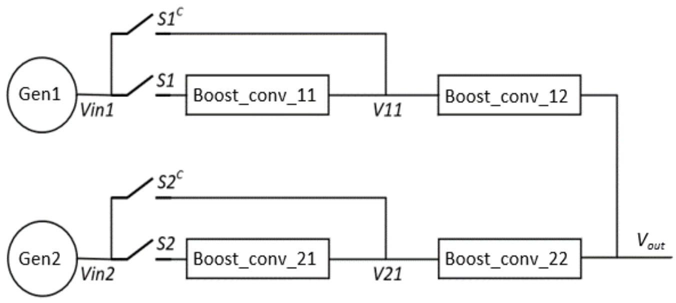

Fig. 4 Block diagram of proposed system.

TABLE I
PARAMETER OF BOOST CONVERTER

Parameter	Value
Load (R)	60 Ω
Switching frequency	5 kHz
$\%V_{ripple}$	< 1%
Inductor (L)	5 mH
Capacitor (C)	500 μF
Transistor (Q)	MOSFET

cascaded configuration. When the converter was operated single, switch S would be open while switch S^C would be closed. Under these conditions, the only converter that worked was the second Boost_conv (Boost_conv_12 and Boost_conv_22). When the converter was operated in series, switch S would be closed, and switch S^C would be open. Under these conditions, the first Boost_conv converter and the second Boost_conv converter worked in series. The connection of two systems in parallel was intended to increase the total power the entire system could generate.

To analyze the system idea, there are four circuit topology designs built in this research, namely the design of a single generator system circuit with one boost converter, which later is referred to as a single converter system; one generator system with two boost converters, which later is referred to as a series converter system; one generator system with two boost converters and a selector, which later is referred to as a cascaded converter system with a selector; and two systems one generator with two boost converters and a selector connected to form a parallel system, which later is referred to as a parallel system. The parallel system is the representation of the system idea. Simulation circuits of a single converter system, a series converter system, and a cascaded converter system with a selector and a parallel system can be seen in Fig. 5 to Fig. 8, respectively. The simulation circuit in the selector circuit block, trigger circuit, and control and trigger circuit can be seen in Fig. 9. The PWM signal generator used in the control and trigger circuit blocks was based on a PI controller with feedback from the converter output voltage. The selector circuit functioned to regulate the opening and closing of switch S.

IV. Results

The simulation was conducted following theories and earlier research studied when conducting a literature review and following the initial simulation. The simulation consisted of a

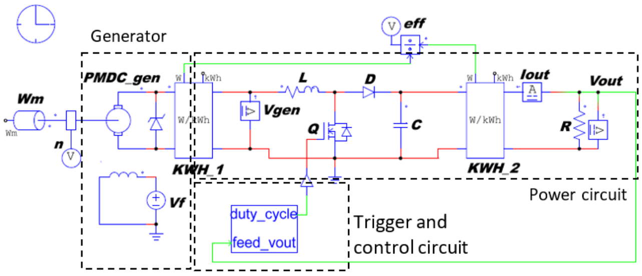

Fig. 5 Simulation circuit of single converter system.

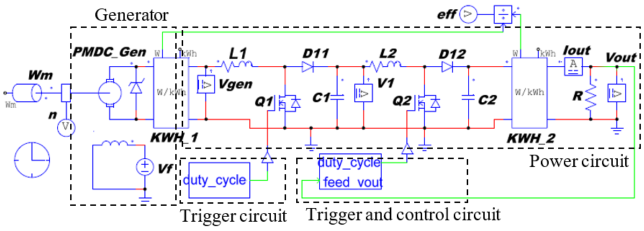

Fig. 6 Simulation circuit of cascaded converters system.

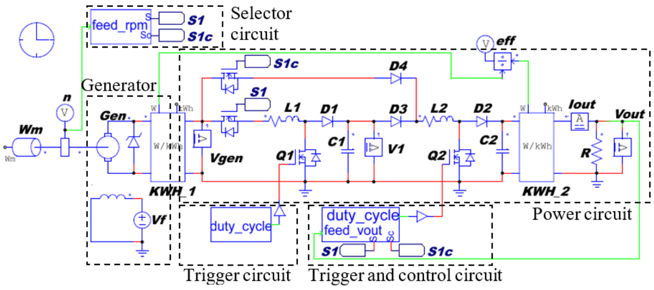

Fig. 7 Simulation circuit of cascaded converters system with a selector.

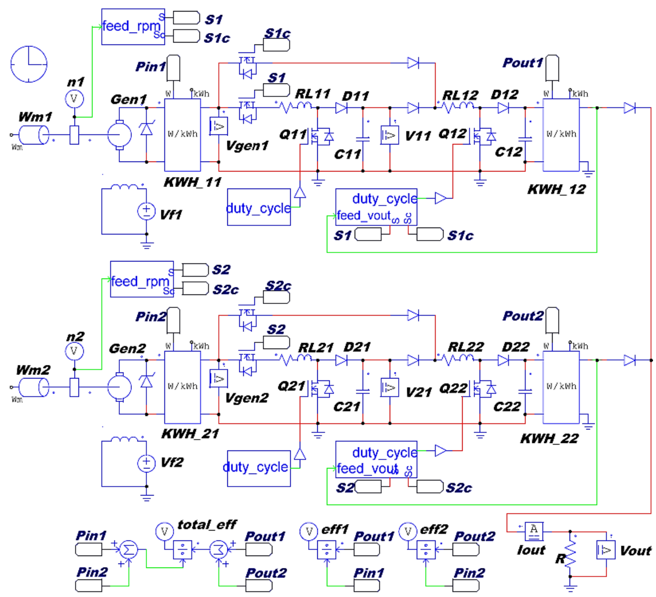

Fig. 8 Simulation circuit of parallel system.

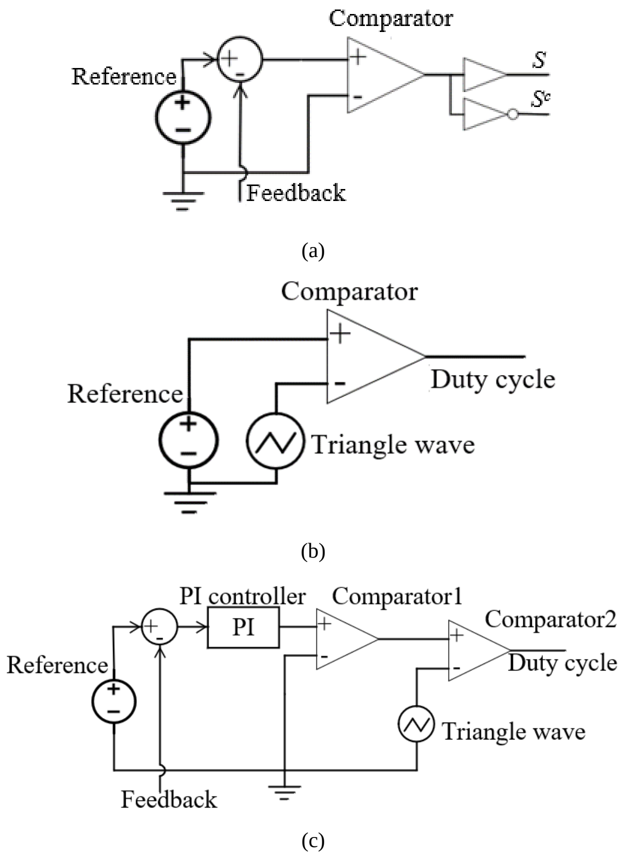

Fig. 9 Electronic circuits used: (a) selector circuit, (b) trigger circuit, (c) control and trigger circuit.

single converter system, a series converter system, a cascaded converter system with a selector, and a parallel system.

A. PWM Signal Generation based on PI controller

It is necessary to control the PWM signal generation to obtain a converter output voltage of 14 V. In this research, the PWM signal generator used is based on a PI controller. Based on the transfer function of the system following (4), and by considering the stability of the system based on the analysis using the Routh-Hurwitz stability concepts in (5) and (6), the value of $kp = 5$ and the value of $ki = 0.5$ or $\tau i = (kp/ki) = 10$.

The results of the simulation of the use of the PI controller on the output voltage of the cascade converter are presented in Table II. The difference in voltage is the difference between the output voltage of the converter and the reference voltage of 14 V. Based on the simulation results, using a PI controller could control the converter to produce a stable output voltage closer to the reference voltage.

B. Single Converter System

Simulation of the single converter system was conducted using simulation circuits, as seen in Fig. 5. In this simulation, the duty cycle value was manually set beforehand to determine the duty cycle limit for the PWM signal generator. As a result, the maximum duty cycle limit of 0.499 was obtained. Thus, the duty cycle value in this single converter system was theoretically limited to 0.499. The system load was 60 Ω. Based on the simulation results, the system could produce a voltage of around 14 V, a current of around 0.233 A, and power of around 3.26 W. The duty cycle at 1,400 rpm was 0.313 and at 1150 rpm was 0.45. The voltage, current, and power values in a single converter system began to decrease significantly at the shaft rotor rotation of 1,210 rpm or lower. It happened since the

TABLE II
OUTPUT VOLTAGE OF CASCADED BOOST CONVERTER WITHOUT AND WITH PI CONTROLLER

Rotor Speed *n* (rpm)	Without PI		With PI	
	V_{out} (V)	Difference (V)	V_{out} (V)	Difference (V)
1,225	14.00349	0.00349	14.00348	0.00348
1,250	14.10018	0.10018	13.99898	0.00102
1,275	14.19838	0.19838	14.00256	0.00256
1,300	14.29343	0.29343	14.00548	0.00548

duty cycle limit was reached. In addition, it could also be caused by the lack of power the generator could generate. The efficiency of the single converter system fluctuated, with an average efficiency at input values of 1,220 rpm to 1,400 rpm was 0.96; at the same time, input values of less than 1,220 rpm to 1,150 rpm yielded average efficiency of 0.91. The efficiency results showed that the single converter system tended to produce higher power efficiency at lower duty cycle values (when the shaft rotor rotation was higher).

C. Cascaded Converter System

Simulation of the cascaded converter system was carried out using the simulation circuit that can be seen in Fig. 6. In this simulation, the duty cycle value was also manually set to determine the duty cycle limit for the PWM signal generator. As a result, the maximum duty cycle limit of 0.360 was obtained. Thus, the duty cycle value of the PWM signal generator in this cascaded converter system was theoretically limited to 0.360 for each converter. The system load was 60 Ω.

Simulation results showed the system could produce a voltage of around 14 V, a current of around 0.233 A, and power of around 3.26 W. At 1,400 rpm, the first and second converters yielded duty cycle values of 0.35 and 0.213, respectively. Meanwhile, at 1.150 rpm, both converters connected in cascaded configuration yielded a duty value of 0.35. The voltage values on the system with a cascaded configuration began to decrease significantly at the rotor shaft rotation of 1,210 rpm or lower. It occurred due to the lack of power that the generator could generate. The efficiency of the cascaded converter system fluctuated, with an average efficiency at input values of 1,220 rpm to 1,400 rpm was approximately 0.93, which is lower than that yielded by the single converter configuration system. However, at input values less than 1,220 rpm to 1,150 rpm, the average efficiency was around 0.92.

Based on the efficiency data obtained from the simulation, it can also be seen that the efficiency values of the single and cascaded converter systems intersected at one point, namely between the shaft rotor rotation of 1,230 rpm and 1,220 rpm, as shown in Fig. 10. Hence, these values were used as references when changing the system configuration.

D. Cascaded Converter System with a Selector

The configuration selector simulation circuit can be seen again in Fig. 9(a). Based on the efficiency values from the simulation of a single and cascaded converter system, which can be seen in Fig. 10, the system would operate in a cascade converter configuration when the shaft rotor rotation was less

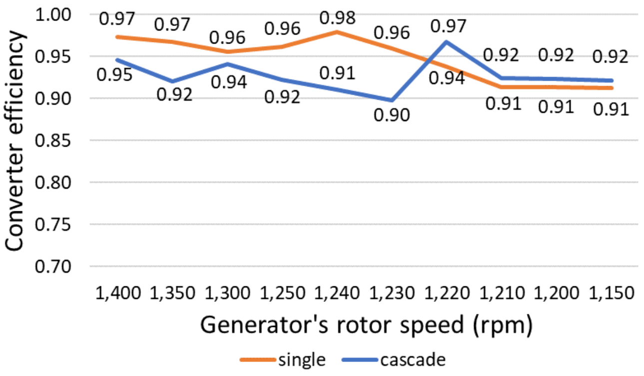

Fig. 10 Simulation result of efficiency of single and cascaded boost converters.

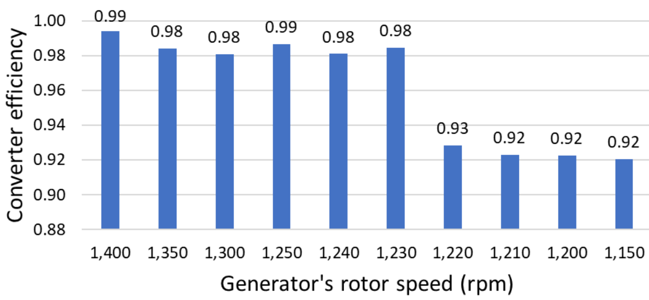

Fig. 11 Simulation results of efficiency of cascaded converters system with selector.

than or equal to 1,220 rpm. When the rotor rotation exceeded 1,220 rpm, the system would operate in a single converter configuration.

Cascaded converter system simulations were conducted using simulation circuits, as portrayed in Fig. 7. With a selector and several additional switches, the two converters utilized in the cascaded converter system might be configured to operate in either single or cascade, according to predetermined criteria. Simulation results demonstrated that the system could produce a voltage of around 14 V, a current of around 0.233 A, and power of around 3.26 W. The voltage, current, and power values dropped at the shaft rotor rotation of 1,230 rpm before rising and beginning to drop significantly at 1,200 rpm. The system efficiency was found to be relatively stable; it was above 0.98 when the shaft rotor rotation was higher than 1,220 rpm and above 0.92 when the shaft rotor rotation was less than or equal to 1,220 rpm. The decrease in efficiency is quite significant. However, compared to a single converter system or a cascaded converter system, the efficiency of the cascaded converter system with a selector is still better in all conditions of rotor rotation, both at high and lower rpm. The efficiency graph of a series converter system with a selector can be seen in Fig. 11.

E. Parallel System

The parallel system comprised two cascaded converter systems with selectors connected and operating in parallel. The parallel system simulation circuit can be seen in Fig. 8. The simulation was carried out in two conditions. The first condition was when the rotation of the generator rotor shaft in

TABLE III
OUTPUT VOLTAGE AND EFFICIENCY OF PARALLEL SYSTEM WITH DIFFERENT RPM INPUT VALUES

Rotor speed *n1* (rpm)	Rotor speed *n2* (rpm)	V_{out} (V)	Efficiency
1,400	1,120	13.727	0.932
1,380	1,140	13.744	0.931
1,360	1,160	13.727	0.930
1,340	1,180	13.735	0.932
1,320	1,200	13.742	0.931
1,300	1,220	13.735	0.928
1,280	1,240	13.742	0.961
1,260	1,260	13.733	0.962
1,240	1,280	13.723	0.961
1,220	1,300	13.757	0.927
1,200	1,320	13.734	0.928
1,180	1,340	13.727	0.931
1,160	1,360	13.735	0.930

each system was different, while the second condition was when the rotation of the generator rotor shaft in each system was the same. The ripple current was around 0.86%, and the ripple voltage was around 0.85%.

The simulation results with the first condition showed the system could generate a voltage of around 14 V, a current of around 0.234 A, and a power of around 3.29 W. The system's total efficiency was relatively stable in the range of 0.93. The efficiency of the parallel system with this first condition can be seen in Table III. It can be seen that the system efficiency tended to be stable at a value of 0.93. However, at similar rpm input values between the two generators, namely, at 1,240 rpm, 1,260 rpm, and 1,280 rpm, there was an increase in efficiency up to 0.96. Due to more balanced load distribution, the two systems were connected in parallel and could work more optimally. The table shows that the greatest efficiency value of 0.962 was obtained when the input value of the two generators was equal to 1,260 rpm. In this case, the input to the system was the value of the rotational speed of the rotor shaft.

The parallel system was then simulated again using the second condition, namely, the input or rotation value of the generator rotor shaft was set the same for both generators. The simulation results showed that the system voltage was maintained at around 14 V even up to the low shaft rotor rotation, which was 950 rpm, which could not be achieved in previous system simulations. It happened since the two generators' generated power and voltage were high enough to supply a load of 60 Ω. Hence, it was possible to amplify up to a higher value at low rotor shaft rotations, enabling the reference voltage to be achieved. The current obtained was around 0.233 A, and the power was around 3.29 W.

There was a slight increase in voltage at the shaft rotation of 1,230 rpm to 1,000 rpm or at the beginning of the configuration of each system, changing from single to cascade. It occurred because the system generated sufficient power to supply the load, so the voltage drop on each generator was not too significant when supporting the load. As a result, only with the initial gain the system voltage already slightly exceeded 14 V.

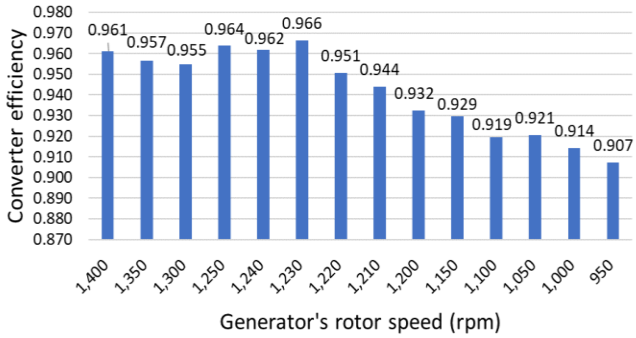

Fig. 12 Simulation result of efficiency of parallel system with same RPM.

TABLE IV
SUMMARY OF EFFICIENCY (η) AND OUTPUT VOLTAGE (V) OF SYSTEM

Rotor speed *n* (rpm)	Single		Cascade		Cascade with a Selector		Parallel	
	η	*V*	η	*V*	η	*V*	η	*V*
1,400	0.97	14.0	0.95	14.0	0.99	14.0	0.96	14.0
1,350	0.97	14.0	0.92	14.0	0.98	14.0	0.96	14.0
1,300	0.96	14.0	0.94	14.0	0.98	14.0	0.96	14.0
1,250	0.96	14.0	0.92	14.0	0.99	14.0	0.96	14.0
1,240	0.98	14.0	0.91	14.0	0.98	13.9	0.96	14.0
1,230	0.96	14.0	0.90	14.0	0.98	13.8	0.97	14.0
1,220	0.94	14.0	0.97	14.0	0.93	14.0	0.95	14.3
1,210	0.91	14.0	0.92	14.0	0.92	14.0	0.94	14.2
1,200	0.91	13.9	0.92	13.9	0.92	13.8	0.93	14.3
1,150	0.91	13.3	0.92	13.3	0.92	13.3	0.93	14.2
1,100	-	-	-	-	-	-	0.92	14.1
1,050	-	-	-	-	-	-	0.92	14.1
1,000	-	-	-	-	-	-	0.91	14.0
950	-	-	-	-	-	-	0.91	14.0

It indicates that, in paralleling the system, it is necessary to readjust the initial gain of the duty cycle value limit to avoid excessive gain. Retuning the configuration selector circuit can also be applied to delay the configuration change until it reaches an even smaller input value.

The system's efficiency was better than the system before operating in parallel; the efficiency could be maintained at a value of more than 0.9 to a low input of 950 rpm, which the system could not achieve before being operated in parallel. The graph of the parallel efficiency system using the second condition can be seen in Fig. 12. Table IV provides a summary of the efficiency and output voltage of a single converter system, a cascaded converter system, a cascaded converter system with a selector, and a parallel system using the second condition operation.

V. CONCLUSION

In a single converter system, it was found that the voltage can be adjusted and maintained according to the desired reference voltage. However, the limit on the duty cycle values and the power that the generator can generate limit the system's ability to maintain the desired output voltage only at the input value of 1,220 rpm to 1,400 rpm. At input values of 1,220 rpm and 1,400 rpm, the average efficiency obtained was 0.96; on the other hand, at input values of 1,220 rpm and 1,150 rpm, the average efficiency obtained was around 0.91. It is in line with previous research that the heavier the boost converter performance (the greater the duty cycle value or, the greater the voltage increase), the greater the tendency for the converter efficiency to decrease.

In the cascaded converter system, the system characteristics in maintaining the output voltage are similar to the single converter configuration system, which was limited when input values were 1,220 rpm to 1,400 rpm. The average efficiency value of the cascade converter configuration at the input values of 1,220 rpm to 1,400 rpm was around 0.93, which is lower than the single converter configuration system. However, at input values less than 1,220 rpm to 1,150 rpm, the average efficiency obtained was about 0.92. This result is higher than that of the single converter configuration system.

In systems that work in parallel (multi-generator, multi-converter), the results showed that the generated voltage could be maintained to a broader input value limit. From the simulation results, the output voltage value was maintained at 14 V to a lower input value of 950 rpm. Likewise, the efficiency value was maintained at a value of more than 0.9 (>90%). Operating the system in parallel requires further tuning so that there is no excessive voltage increase in the system due to the generated power being too large to support the load previously, which is previously supported by one system.

CONFLICT OF INTEREST

Authors declare no conflict of interest in this reseach.

AUTHOR CONTRIBUTION

Conceptualization, Rizki Nurilyas Ahmad, Mochammad Facta, and Iwan Setiawan; methodology, Rizki Nurilyas Ahmad; software, Rizki Nurilyas Ahmad; validation, Rizki Nurilyas Ahmad, Mochammad Facta, and Iwan Setiawan; formal analysis, Rizki Nurilyas Ahmad; investigation, Rizki Nurilyas Ahmad; resources, Rizki Nurilyas Ahmad; data curation, Rizki Nurilyas Ahmad; writing—original draft preparation, Rizki Nurilyas Ahmad; writing—review and editing, Rizki Nurilyas Ahmad.

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