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Optimization improvement using Pi controller to reach CCCV method in lead acid battery load

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Abstract

Solar energy can produce electrical energy with the help of photovoltaics so as to produce sufficient or even excessive supply to the electrical load. Therefore, it is necessary to store electrical energy (battery) from the excess unused energy. However, in the process of charging the battery, it takes a long time to fully charge the battery capacity and damage often occurs due to excessive voltage used. This can reduce battery life. The characteristics of the battery need to be considered so that the charging process can be carried out in accordance with the required provisions. The existence of the CCCV method can speed up the battery charging process with a constant current of 20% of the nominal current of the lead acid battery. To avoid overvoltage, the constant voltage method can anticipate the occurrence of damage. Utilization CUK Converter as charging can reduce output voltage ripple. The PI control on the CUK Converter produces a constant voltage of 13.8 Volts and a constant current of 1.44 Ampere. The average error generated by this system is 0.14%.

1. Introduction

The use of energy to meet the needs of human life is very important in the economic growth of a country. Currently, power plants still use fossil fuels which are relatively expensive and cause environmental pollution. Fossil fuels in the world are running low, so it is necessary to look for alternative energy. [1] Of the various alternative energies that are also included in renewable energy such as water, wind, biomass and others, the sun is an alternative energy that is easy to obtain and good for the environment. [2] [3] The use of solar energy is the state-of-the-art field indeed a solution, it's just that the sunlight received by solar cells will not always be stable depending on conditions and weather. It is strongly influenced by the characteristics of solar cells. [4] The use of solar cells in Indonesia is strongly supported because it has a tropical climate. Recently, the Government of Indonesia has allocated Rp 1.4 trillion for the development of various renewable energies, including the installation of solar cells or solar panels in government offices, airports, and prisons. [5] The use of solar cells can meet the needs of even excessive electrical loads. Therefore, a battery is needed to store the energy produced during the irradiation process and when the solar cell does not receive solar radiation. The battery used is a battery that can be recharged by an electric charge (*rechargeable*), so it is necessary to pay attention to the treatment of voltage and current in the charging and discharging process according to the characteristics of the battery. [6] Excessive charging and discharging (overcharge abd overdrain) can cause the battery to be damaged quickly and energy utilization is not optimal. [7] [8]

The use of converters as a battery charging process is very often done. Each converter has its own characteristics. There are several types of dc-dc converters, including buck, boost, or buck-boost. The CUK converter topology works like a buck-boost converter which can increase and decrease the output voltage. [9]. Batteries are very susceptible to changes in volage values during the charging process so that the selesction of the CUK converter is due to having higher efficiency characteristics and can reduce ripple from the output. [10] [11] So that the use of the CUK converter as a battery charging device is very suitable, the battery used is of the lead acid type. For the charging process, there are several methods, one of which is recommended for charging lead acid batteries is the CCCV (*constant current-constant voltage*) method. [12] [13] [14] The constant current method at the beginning of charging the battery until the voltage in the battery reaches a certain value then changes to the constant voltage method until the initially constant current drops to near zero. [15] [16] [17]

Therefore, the design of the CUK converter as a current and voltage stabilizer can be used for charging the battery with the help of PI control. PI control can help stabilize output and minimize overshoot. [18] [19] PI control too used to achieve and maintain parameter reference values by correcting *errors.* [20] This is done so that the CCCV method can work and the existence of this method can speed up battery charging and reduce the occurrence of excess voltage that can damage the battery. [21]

In this study, the charging process uses a source from 100 WP solar cells. The output of the solar cell will be the source of the CUK converter and the output of the CUK converter as a regulator of the incoming voltage and current values as *supply* batteryThe current sensor and voltage sensor will be read before the CUK converter and after or the output from the CUK converter. The data read will be processed by the microcontroller using the PI algorithm, after that the microcontroller will send data in the form of PWM to the driver which will control the voltage value on the CUK converter so that the voltage value corresponds to the 13.8 Volt set point. In this test, using the CUK converter design calculation, the battery used is 12 Volt 7.2 Ah. So that the system design is compatible between devices and can be integrated in a good performance.

2. Research Method

In this stage, the CUK converter acts as a battery charger with a constant current constant voltage method using a solar panel source. In the design and manufacture of systems consisting of solar panels, lead acid batteries, CUK converter modules and PI control designs can be seen in Figure 1.

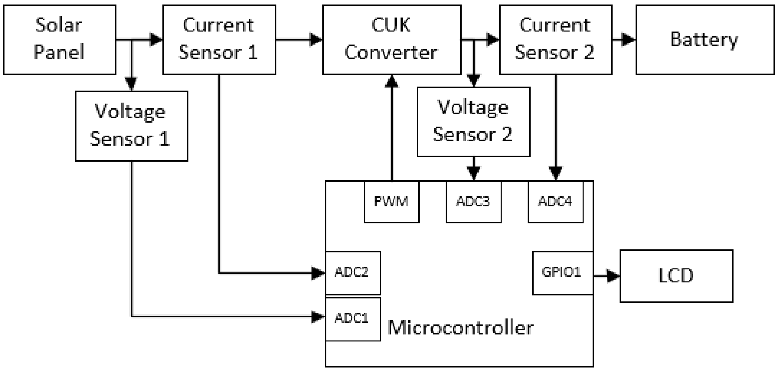


Figure 1. Overall System Block Diagram

2.1 Photovoltaic Module

In general, the working principle of solar cells is to convert the intensity of sunlight into electrical energy. The electrical power produced by the solar cell when it gets light is obtained from the ability of the solar cell device to produce a voltage when it is given a load and at the same time a current through the load. This capability is represented in the current-voltage (IV) curve. Curve IV consists of 2 important things:

1. Maximum Power Point (Vmp and Imp) is the operating point, where the maximum output / output generated by the solar cell during operational conditions. In other words, Vmp and Imp can be measured when the solar cell is loaded at a temperature of 25ºC and a radiation of 1000 W/m^2.
2. Open Circuit Voltage (Voc) is the maximum voltage capacity that can be achieved when there is no current or open circuit.

At the Table 1. shows the parameter data for solar panels with a peak power of 100 Watts below. The specification of solar panels is compatible with design of CUK Converter.

Table 1. Specification of Photovoltaic

Parmeters	Value
Maximum Power (Pmax)	100 W
Current at Pmax (Imp)	5.72 A
Voltage at Pmax(Vmp)	17.5 V
Short circuit Current(Isc)	6.35 A
Open circuit Voltage(Voc)	22.0 V

2.2 Lead Acid Battery

Battery is an electric cell device in which the electrochemical process takes place in a reversible manner with high efficiency. Lead acid batteries are batteries for solar panel systems that use Lead Acid as the chemical. Lead acid batteries are strongly recommended using the constant current constant voltage (CCCV) charging method. The battery used in this test has a capacity of 12V 7.2 Ah according to the previous converter design.

Batteries have a capacity when used per hour which is known as AH (Ampere-Hour). In charging the battery there is a standard level where the battery can be said to be full. The battery voltage when fully charged has a value above 15%-25% of the battery voltage rating. In charging the battery there are conditions that must be met so that the charging can run properly, namely: The charging voltage level must be higher than the battery voltage level. The charging current should be kept around 10% - 30% of the battery capacity. [22]

Efficient battery operation is directly correlated with the accuracy of the State of Charge (SoC) estimation. The meaning of State of Charge (SoC) is the percentage of remaining battery capacity.

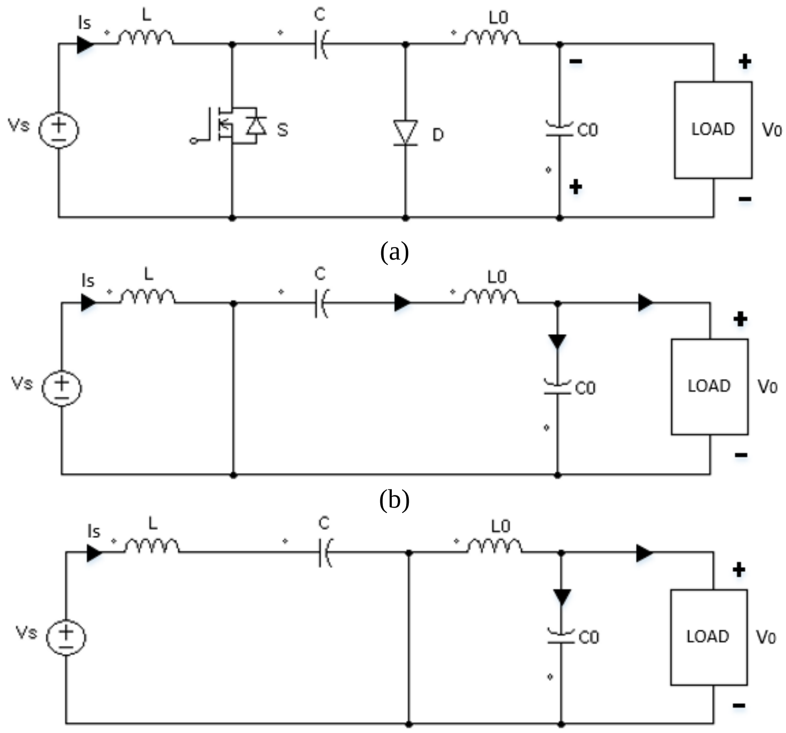
To measure the State of Charge (SoC) of a battery, the following 3 methods can be used, namely:

1. Direct measurement, can be done if the battery can be charged with a constant value.
2. SoC from the measurement of Specific Gravity (SG), this method depends on changes in the weight measurement of the active chemical.
3. SoC estimation based on voltage is done by measuring battery cell voltage as a basis for calculating SoC or remaining capacity. [23] [24]

2.3 Modeling CUK Converter

The converter circuit in this project system functions as a voltage controller from the solar cell to the battery charging load, but the most important thing in this project is to set the duty cycle value to produce a constant current. voltage according to the set point. The CUK converter has advantages over other dc-dc converters, such as high-voltage amplifier capability, continuous input current, low EMI generation and high efficiency. [25]

Basically the components used are the same as other converters in general, namely inductors, capacitors, diodes, and switching transistors. The basic circuit of the CUK converter is shown in Figure 2.



(c)

Figure 2. (a) CUK Converter Topology (b) CUK Converter Switch On (c) CUK Converter Switch Off

From Figure 2 (a) it is a circuit in the CUK converter in general. The CUK topology can produce smaller current ripples than the buck-boost topology, because it has 2 inductors and 2 capacitors. The CUK converter itself consists of two inductors (L and L0), a coupling capacitor (C), an output capacitor (C0) and two switches, namely S (IGBT or MOSFET) and D (diode). The operation of the CUK converter circuit can be divided into two conditions, namely the switch S on and off. Figure 2(b) shows that when the switch S is on, the diode D will be reverse biased and the current through the inductor L will increase. It was found that the current L (Inductor 1) is equal to the current C (Capacitor 1). Figure 2(c) shows when switch S is turned off, the inductor will release energy so that the diode will be forward biased and energy will be sent to both capacitors. The current in inductor L0 (Inductor2) is the same as capacitor C (Capacitor 1).

From the circuit and working method above, it can be determined to find the value of the system's duty cycle assuming the initial value of the duty cycle is 100%. The duty cycle is the switch ratio, so the following equation is obtained. The result of this equation is similar to that of a buck-boost converter, with the difference being that there is a negative sign (-) indicating that there is an inverted polarity between the input and output voltages [26].

$$D = -(\frac{Vout}{Vout + Vin}) \tag{1}$$

And from some of the specified parameters, other parameter values can be searched using the following Equation 1, Equation 2, Equation 3, Equation 4, Equation 5, Equation 6, Equation 7, Equation 8, and Equation 9 [27].

$$\Delta \mathrm{IL}_1 = 20\% \,.\, \mathrm{Iin} \tag{2}$$

$$\Delta \mathrm{IL}_2 = 20\% \,.\, \mathrm{Iout} \tag{3}$$

$$\mathrm{L1} = \frac{\mathrm{Vin}\,.\,\mathrm{D}}{\Delta \mathrm{IL}_1\,.\,\mathrm{f}} \tag{4}$$

$$\mathrm{L2} = \frac{\mathrm{Vin}\,.\,\mathrm{D}}{\Delta \mathrm{IL}_2\,.\,\mathrm{f}} \tag{5}$$

$$\mathrm{IL}_{1\,rms} = \sqrt{\mathrm{Iin}^2 + \left(\frac{\Delta \mathrm{IL}/2}{\sqrt{3}}\right)^2} \tag{6}$$

$$\mathrm{IL}_{2\,rms} = \sqrt{\mathrm{Iout}^2 + \left(\frac{\Delta \mathrm{IL}/2}{\sqrt{3}}\right)^2} \tag{7}$$

$$C_1 = \frac{Vout\,.\,D}{R\,.\,\Delta \mathrm{Vc1}\,.\,\mathrm{f}} \tag{8}$$

$$C2 = \frac{(1-D)}{(\Delta \mathrm{Vo}/\mathrm{Vout})8\,.\,L2\,.\,f^2} \tag{9}$$

Description:

Vin	= Input Voltage (V)
Vout	= Output Voltage (V)
D	= Duty Cycle
I_L	= Load Current (A)
I_{in}	= Input Current (A)
I_{out}	= Output Current (A)
L	= Inductor (H)
F	= Switching Frequency (Hz)
R	= Resistance (ohm)
ΔIL	= Inductor Ripple Current (A)
$I_{(L\ rms)}$	= Inductor RMS Current (A)
C	= Capacitor (F)
ΔV_o	= Ripple Output Voltage (V)
ΔV_{c1}	= Ripple Rasio Input and Output Voltage (V)

Table 2. Results of CUK Converter Component Calculations

Parameters	Symbol	Value	Units
Input voltage	V_{in}	17.5	Volt
Output voltage	V_{out}	13.8	Volt
Input Current	I_{in}	5.72	A

Ouput Current	I_{out}	1.44	A
Switching Frequency	F_{sw}	40	Khz
Inductor Ripple Current 1	ΔIL_1	1.144	A
Inductor Ripple Current 2	ΔIL_2	0.288	A
Inductor 1	L_1	168	uH
Inductor 2	L_2	668	uH
Inductor RMS Current 1	$I_{L\ rms1}$	6.292	A
Inductor RMS Current 2	$I_{L\ rms2}$	1.584	A
Voltage ripple	ΔV_o	0.014	Volt
Voltage ripple 1	ΔV_{c1}	0.031	Volt
Capacitor 1	C_1	505.2	uF
Capacitor 2	C_2	65.5	uF

Table 2 shows the data from the calculation of the component design for CUK Converter. the result of the component value according to the above formula calculation.

2.4 Modelling PI Controller

In this project to determine the value of PI control design using analytical methods. The PI control function serves to maintain the stability of the output voltage of the CUK converter. To determine Kp and Ki, it is necessary to find the following parameters Equation 10, Equation 11, Equation 12, Equation 13, Equation 14, Equation 15, Equation 16, and Equation 17.

$$K = \frac{Yss}{Xss} \tag{2}$$

$$\tau_s = 5\tau \tag{3}$$

$$\tau_s = \alpha\tau_s^* \tag{4}$$

$$\tau_s^* = 5\tau^* \tag{5}$$

$$\tau_i = \tau \tag{6}$$

$$\tau^* = \frac{\tau_i}{K_p \times K} \tag{7}$$

$$K_p = \frac{\tau_i}{\tau^* \times K} \tag{8}$$

$$K_i = \frac{K_p}{\tau_i} \tag{9}$$

To find value of Kp and Ki in each other parameter with the formulas, there are 2 parameters must be solve it shown results bellow.

Voltage	
Ts	0.02
Tr	0.006
Value Steady	12.77 Volt
Setting Point	13.8 Volt
K_i	1351.25
K	0.925
τ	0.004
τ_s^*	0.004
τ^*	0.0008
K_p	5.405
K	0.923

Current	
Ts	0.03
Tr	0.006
Value Steady	1.33 Ampere
Setting Point	1.44 Ampere
τ	0.0006
$\tau_s{}^*$	0.0006
τ^*	0.0012
K_p	5.417
K_i	902.83

3. Results and Discussion

In this section, the author explains the results system testing and analysis of simulation test results. Testing aims to find out how the system works and see the level of success of the system according to predetermined specifications.

3.1 CUK Converter Simulation Test

The CUK converter is used as a battery charger with a battery capacity of 12V 7.2 Ah. Simulation experiment aims to see the results or performance of the CUK converter with PI control. In Figure 3 it can be seen that the circuit made requires 1 PV with 100 WP specifications as a source to supply the CUK converter. From the results of the PV simulation, the output voltage value is 17.5 V and the output current is 5.72 A. This simulation is carried out using Matlab software for better accuracy. Using 2 PI controls with different purposes, the first is for the current constant with a set point of 1.44 A and the second is for the voltage constant with a set point of 13.8 V.

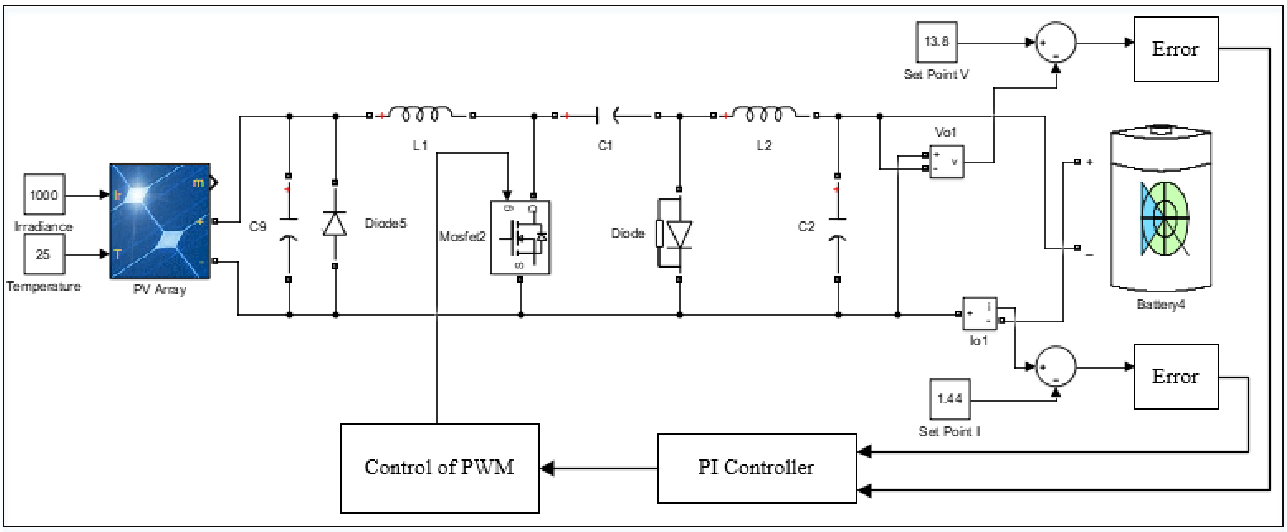


Figure 3. Closed Loop CUK Converter Circuit

To see the performance of the CUK converter in the battery charging process, integration testing can be carried out on the simulation with see the value of State of charge (Soc), voltage, and current on the battery. In this simulation using a duty cycle value of 44% in accordance with the design calculations that have been made. From the simulation results, the response without control makes the CUK converter like a buck converter system. It can be compared from the journal " perancangan sistem tegangan dan arus terkendali (*constant voltage* dan *constant current*) berbasis kontrol pid " [12], with the use of PID control which has a longer rise and settling time than the simulation results in this journal.

Table 3. PI Control Perfomance Response

Control System		Rise Time (s)	Settling Time (s)	Set Point	Steady State	Steady State Error (%)
		Output Parameter Response				
Voltage	Open Loop	0.006	0.02	13.8	12.77	7.46
	Close Loop	0.008	0.014	13.8	13.8	0

Current	Open Loop	0.006	0.03	1.44	1.33	7.64
	Close Loop	0.008	0.023	1.44	1.44	0

From the comparison Table 3, it can be seen that the CUK converter simulation with PI control has a longer rise time value than the CUK converter simulation without control, but the settling time value of the CUK converter with PI control is faster than the CUK converter simulation without control. In the open loop condition or the uncontrolled CUK converter simulation, the error percentage value is 7.64%.

If the PI control system does not work, the CCCV method cannot run. It also can cause the battery to be demaged quickly. By implementing this system, you can charge the battery effectively and efficiently.

3.2 System Integration Hardware Result

CUK Converter test using a solar cell input of 100 WP using a PI control to adjust the duty cycle is shown in Figure 4. Testing using a 12V 7.2 Ah VRLA battery load.

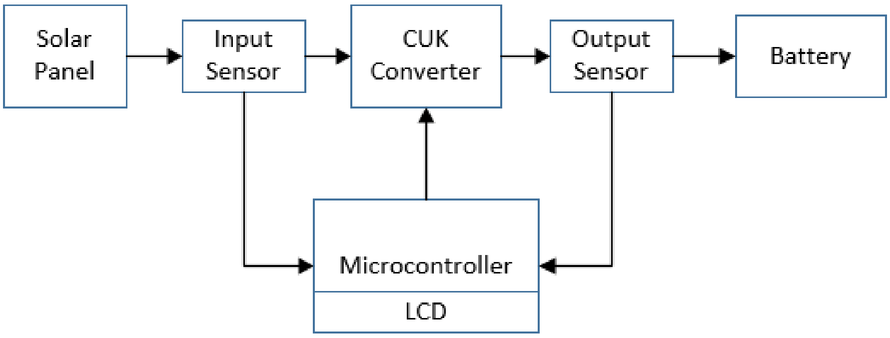


Figure 4. Overall Hardware System

Result of testing the integration of the load system using a battery is that the battery charging process is carried out with a battery SoC of about 50%. The results of the hardware system integration can be seen in Figure 5. Where in real testing for more than 3 hours, from 10.00 a.m. until 01.20 p.m., Data collection was carried out in several experiments by taking the best data values on several similar results with similar experimental conditions. The constant current method is obtained at the beginning of charging the battery and after it switches to a constant voltage method until the battery is fully charged with a current indicator that continues to decrease to close to 0 amperes.

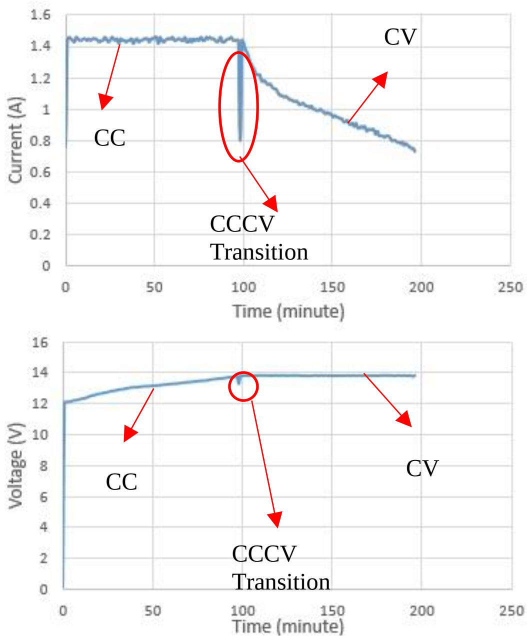


Figure 5. Constant Current Constant Voltage Transition

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From Figure 5 the graph shows that the constant current constant voltage (CCCV) method system runs as desired with a constant current value of 1.44 amperes and a constant voltage of 13.8 volts. From Figure 5 it can be transformed into data in the form of a table which will later get the average error value for the current and voltage values of around 0.14% according to each set point. The graph above is based on the time during the battery charging process.

From the journal “Perancangan Sistem Tegangan dan Arus Terkendali (Constant Voltage dan Constant Current) Berbasis Kontrol PID” [12] the PID system by controlling the buck converter on the battery SoC about 50-60% takes approximately 3 hours and using the CCCV method produces an error value between 0.24% - 0.29%. From the journal “CC-CV Controlled Fast Charging Using Fuzzy Type-2 for Battery Lithium-Ion” [15] the use of the CCCV method in the fast charging process on the battery produces an error between 0.83% - 1%. So with this journal, it can improve the optimization in the CCCV method process in charging the battery with a fairly fast charging time and a smaller average error than the previous experiment.

4. Conclusion

After testing the tool, the author can conclude that the CUK converter as a battery charger works very well and can be the answer to the problem of energy storage in the battery. This system can also produce constant current constant voltage according to the method used. The PI control makes a constant current with a value of 1.44 Amperes and a constant voltage with a value of 13.8 Volts. So the optimazition CCCV method that the *charging* with PI control gets an average *error* 0.14% or close to the *set point* of constant current and constant voltage.

Notation

V : Voltage
A : Ampere
Khz : Frequency in kilohertz
μH : MicroHenry
μF : MicroFarad
W : Watt
WP : WattPeak
Ah : Ampere-Hour
W/m^2: Watt permeter cubic
ºC : Temperarture in Celcius

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