Design of Digital Control Algorithms for Multi-Input Multi-Output Switching Converters Used in Energy Harvesting Applications

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Abstract: A single-inductor dual-input triple-output converter is designed by MATLAB software in this article, which can be used in energy harvesting systems where the goal is to reduce battery usage to increase battery life. Input other than one connected to a battery can be virtually any source that can generate energy, such as a thermoelectric generator (TEG). In this converter, when the energy level of the first input is low, another input (battery) is used. This converter works in DCM and uses pulse width modulation control. This converter works using the time-multiplexing control method, which makes the cross-regulation problem between the outputs of this converter very small. In the control algorithm considered in this converter, a zero current detector is used to determine the optimal discharge duty cycles. Also, the switching frequency in this converter may differ for each output, and the maximum switching frequency in this converter is relatively low, equal to 5kHz.

Keywords: energy harvesting (EH), time-multiplexing control (TMC), cross-regulation, zero current detector (ZCD).

I. Introduction

Energy harvesting technology is a solution for power supply in low-power systems such as internet of things (IoT) devices, wireless sensors, RF transceivers, wearable electronic devices, etc. The significant point here is that this can increase battery life and help the development of battery-free systems. The energy sources used in the power management systems of these devices can be renewable energy sources such as a photovoltaic cell (PV) and thermoelectric generator (TEG), which can convert light and heat energy into DC voltage, respectively. This reduces battery usage. Some of the systems mentioned earlier require multiple independent supply voltages; thus, a power management system is needed to generate these voltages.

DC-DC switching converters of multiple-input-single-inductor-multiple-output (MISIMO) type were introduced (Fig. 1) to increase the attainable power and power density using multiple EH sources and multiple loads conduction [1]-[4].

These converters also have a convenient and cost-effective structure of multiple switching converters. In this type of converters, due to being a single inductor, which reduces the number of switching components, the rate of losses due to the switching is lower. These converters mainly work in discontinuous conduction mode (DCM). Due to these specifications, this converter has high efficiency and has a smaller size.

Due to the multiple outputs in this type of converter, a cross-regulation effect occurs between the outputs, which harshly affects the voltage regulator operation. Even under certain conditions, it may lead to system instability. Cross-regulation has been studied in several references [1]-[5], and various control methods have been proposed to improve it. However, the challenges of MISIMO converters remain.

This paper proposes a converter to solve this problem, which operates in discontinuous conduction mode (DCM) using the time-multiplexing control (TMC) method. Also, using pulse width modulation (PWM) and lowering the switching frequency, the output voltages are charged independently with different frequencies when the corresponding switch is turned on. This control method completely solves the cross-regulation problem to some extent.

This proposed converter is simulated in MATLAB, and has three outputs and two inputs (Fig. 2), and each of these three outputs can work in three modes of buck, buck-boost, and boost. One of the inputs is considered connected to the battery, and the other can be connected to any source that can produce energy; for example, this source can be a thermoelectric generator (TEG) [4], and here, only one of these two sources according to the energy level and priority specified in the system is used to charge the outputs.

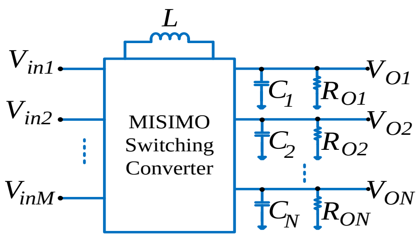

Fig. 1: Power management system. MISIMO switching converter.

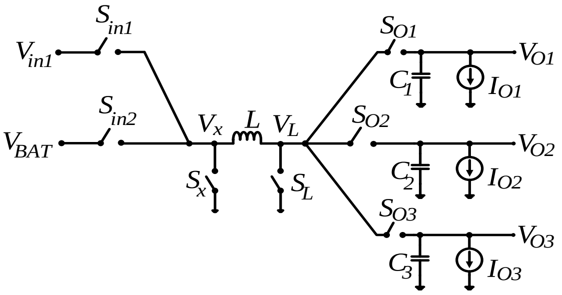

Fig. 2: MISIMO converter presented in this paper.

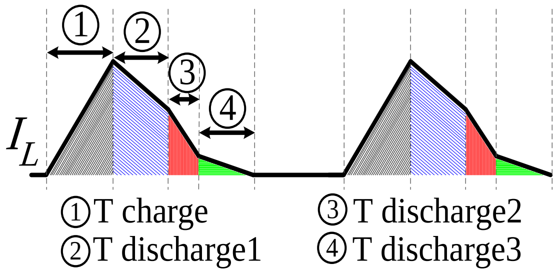

Fig. 3: Converter with OPDC control scheme.

The third output is used as a battery charger when the input energy level other than the battery is above the specified range.

The low switching frequency of the converter, which maximum switching frequency is equal to 5 kHz, and its usefulness in low-power systems, since the output voltages and loads are not high, are among the capabilities of this converter. Due to the converter's performance in DCM and having three outputs, it is necessary to consider the appropriate phase shift for PWM signals. The aim here is to design an algorithm that can determine the optimal charge duty cycle considering the low switching frequency and work in three modes: buck, buck-boost, and boost.

The rest of this paper is organized as follows: Section II provides review of OPDC and TMC in DCM operation, and Section III describes the circuit implementation and control algorithm. Section IV presents the simulation results in MATLAB software, and finally the conclusion is given in Section V.

II. Review of OPDC and TMC in DCM

To understand how MISIMO converter works, it is necessary to have a background discussed in this section. Various methods have been studied in the literature to control a DC-DC converter. One of the prevalent methods is called ordered power-distributive control (OPDC), in which the inductor current is charged and then discharged at different outputs, as shown in Fig. 3 [6], [7]. When there is some current flowing in the inductor, one switch must be turned off, and another switch turns on, which increases the switches' resistance momentarily that cause power wasting in this technique. Also, cross-regulation can be seen entirely in this method.

The method used in this paper is a type of time-multiplexing control (TMC). One of the advantages of the TMC method, as mentioned, is that each output has a separate charge and discharge time. On the other hand, due to the multi-output of some converters, there are several problems, one of which is to determine the appropriate phase shift for each output. On the other hand, choosing the proper phase shift becomes very difficult if each output operates at a different frequency. Therefore, these phase shifts between the PWM signals of each converter switch must be considered so that each output is charged and discharged independently, and there is no overlap between the other outputs. In this converter, since the current value of each output is low, considering the appropriate phase shift, there is no need to worry about signal interference. Fig. 4 shows a timing diagram for the switches of this converter. In Fig. 4, the switching frequency is assumed to be constant for each output. The first, second, and third output charging and discharging phases are ϕ_α, ϕ_β, and ϕ_φ, respectively. D_{1x} and D_{2x} (x = α, β, φ) correspond to the charge and discharge duty cycles of each output, respectively.

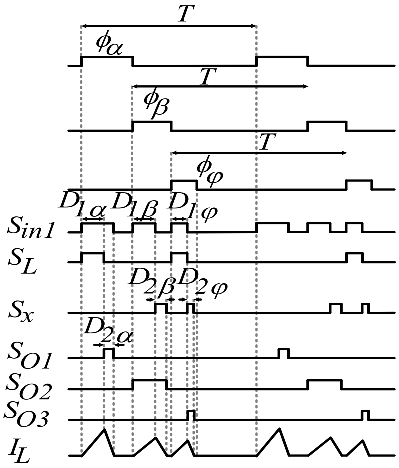

Fig. 4: The timing diagram of this MISIMO converter in DCM operation. First output, second output and third output work in boost, buck and buck-boost mode, respectively.

Fig. 4 shows the inductor current waveforms (I_L) and the signals applied to the circuit's input and output switches in Fig. 2. This method increases efficiency and also eliminates cross-regulation. Another problem with this method is the need for a circuit to detect zero inductor current (ZCD).

This converter works in buck, buck-boost, and boost modes. Depending on the mode, certain switches turn on and off. The desired input and output switches are turned on first in the buck mode, and the inductor current increases. Then, in the next phase, the S_x switch is turned on to discharge the inductor current, and the current is discharged by placing a negative voltage on the inductor. In buck-boost mode, the desired input switch and the S_L are turned on first, the inductor current increases, and then in the inductor current discharge phase, the desired output switch and the S_x switch are turned on. In boost mode, to increase the inductor current, it has been acted like buck-boost mode. Only for the inductor current discharge phase to create a negative voltage on the inductor, instead of turning on the S_x switch, the corresponding input switch also remains on.

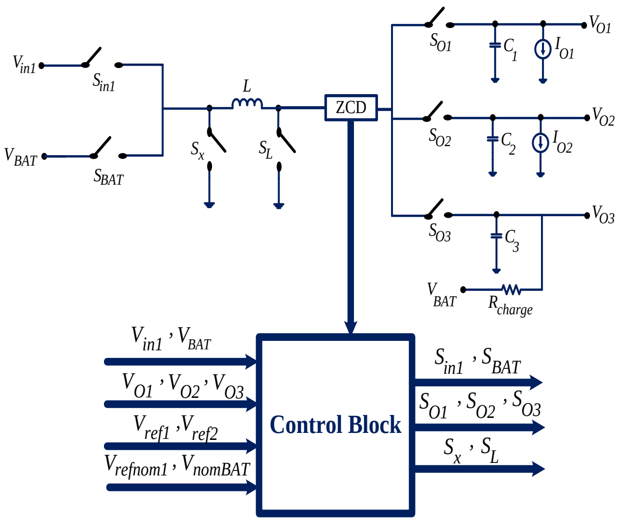

Fig. 5: Simplified diagram of the proposed MISIMO converter.

III. Control Algorithm of the Proposed Converter

The diagram of proposed converter and the control algorithm are shown in Fig. 5 and Fig. 6, respectively.

The algorithm (Fig. 6) shows that the output voltages and input voltage read by control block every t msec. By using the last value of the output voltage, the error value is obtained according to (1). By using the error value brought according to (2), which is presented in discrete, the inductor charging duty cycle D1x is determined [8], [9].

$$error = V_{ref} - V'_{OS} \tag{1}$$

$$D_1 = K_p * error + \sum K_i * error \tag{2}$$

Here, the first and second output voltages are compared with the specified reference voltages of $V_{ref\,1}$ and $V_{ref\,2}$, respectively, and according to the values of K_p and K_i considered for each mode (buck, buck-boost, and boost), the inductor charge duty cycle is calculated.

As mentioned, this converter has two inputs, and here the algorithm is such that the second input connected to the battery has the least possible use. Therefore, when the energy level of the first input is higher than the minimum limit set for it, it can be used to charge the outputs. If it is higher than the maximum limit set for it, in addition to charging the outputs, it can be used to charge the battery. These minimum (ρ) and maximum (λ) limits are 70% and 90% of the nominal voltage ($V_{refnom1}$) of this input, respectively. Otherwise, the battery is used to charge the outputs. Fig. 7 shows the desired input algorithm.

Charging the battery is done with constant current (CC) and constant voltage (CV) methods. The constant current method is used when the battery voltage is less than λ_{BAT}. λ_{BAT} is a percentage of the nominal voltage value of the battery (V_{nomBAT}) based on the battery datasheet, which is about 80% here. Also, when the battery voltage reaches or exceeds λ_{BAT}, the charging method would be constant voltage.

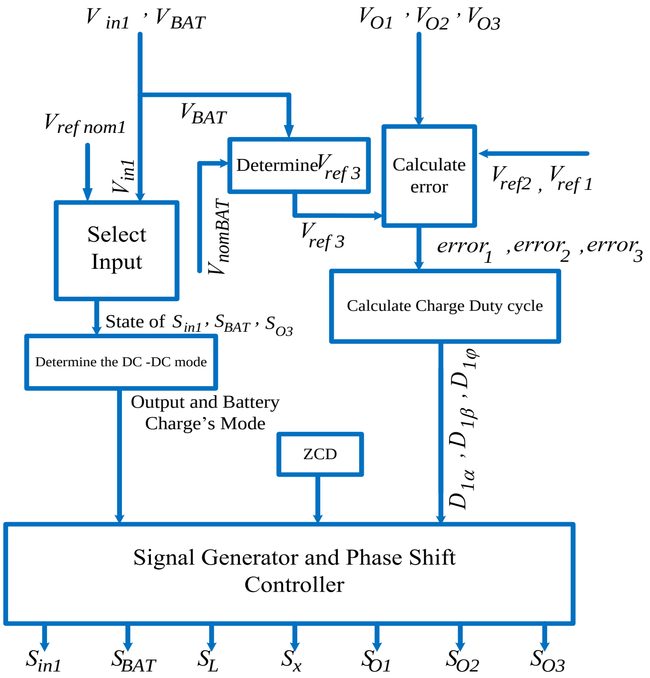

Fig. 6: Proposed Control Algorithm.

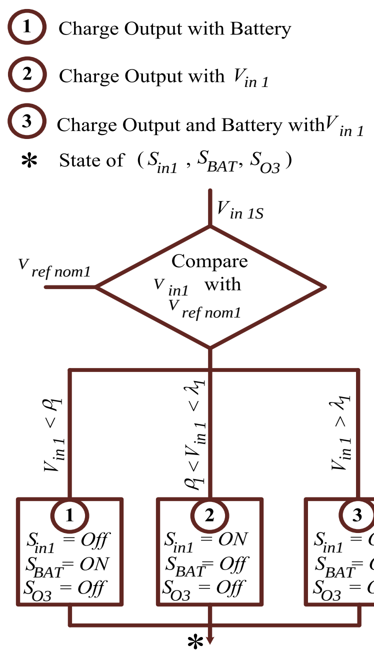

Fig. 7: Select desire input.

As mentioned, the third output is selected to charge the battery, so the reference voltage of the third output ($V_{ref\,3}$) should be determined according to the battery voltage status. Here, when the system is charging the battery with the constant current method, the value of the third output voltage is greater than the battery voltage as much as C, which is a constant number. C is the amount of voltage across the charging resistor (R_{charge}) set here to be 0.2V. The third output voltage value in the constant voltage method is constant and equal to V_{nomBAT} . Fig. 8 shows this algorithm.

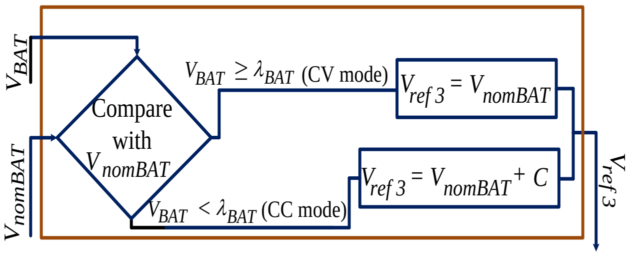

Fig. 8: Determine the reference voltage for battery charging mode.

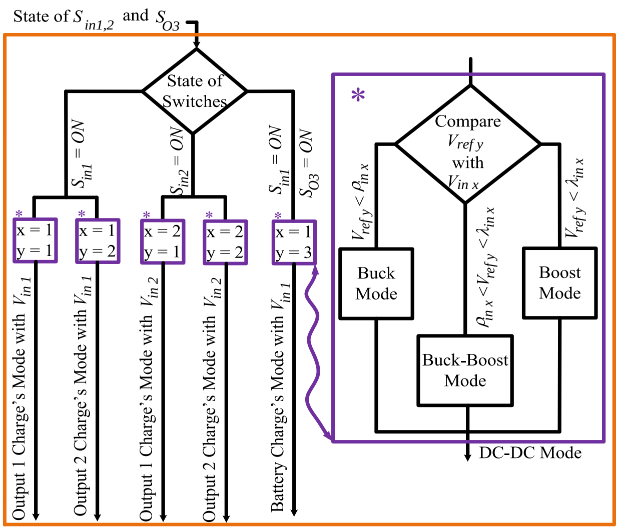

Fig. 9: Determine DC-DC mode algorithm.

The reference voltages of each output are compared with the value of the selected input voltage to determine the output voltage mode. Based on this comparison, the mode of each output (buck, buck-boost, and boost) is determined. The value of the inductor discharge duty cycle is also determined according to the output voltage mode and based on a coefficient of the charge duty cycle. The algorithm for determining the output voltage mode is shown in Fig. 9. Here, if the reference voltage is less than ρ_{in} , the converter operates in buck mode, and if it is greater than λ_{in} , it works in boost mode, and if it is between ρ_{in} and λ_{in} , it operates in buck-boost mode.

λ_{in} and ρ_{in} are coefficients of the input voltage, which here are $1.1V_{in}$ and $0.9V_{in}$, respectively.

Then, PWM signals are selected for the respective switches according to the charge and discharge duty cycles. ZCD is used such that as soon as the inductor current is zero, the switch turns off the output. The critical point here is that the considered phase shift should be such that each of the three outputs can have its own independent charging and discharging time, and these signals are entirely non-overlap.

When the outputs have equal switching frequency, the phase shift value can be determined in terms of the power drawn from each of them.

Suppose the converter is charging the first and second outputs, and as we know, the power is proportional to the time

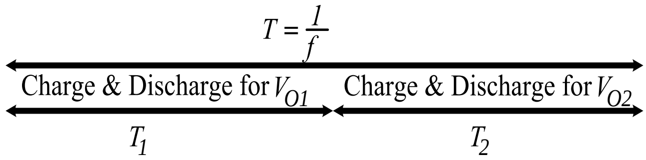

Fig. 10: Considered phase shift based on output power.

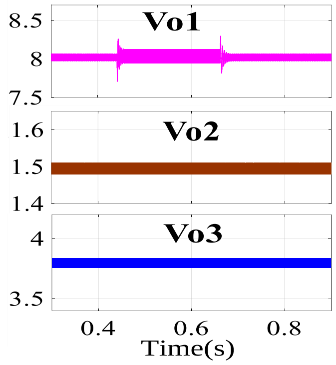

Fig. 11: Simulink simulation. output voltages. I_{o1} = 10 mA, I_{o2} = 5 mA., I_{o3} = 40 mA and f_s = 5 kHz.

square ($P \propto t^2$). If the periodicity is assumed to be T, the amount of phase assigned to each output can be considered proportional to the $\sqrt{Power}$ drawn from that output. Fig. 10 and (3) also show the range for charging and discharging each output.

$$T_1 = \sqrt{\frac{Power_1}{Power_{total}}} \times T \quad , \quad T_2 = \sqrt{\frac{Power_2}{Power_{total}}} \times T \tag{3}$$

IV. Simulation Results in MATLAB

The proposed MISIMO is simulated in MATLAB software. The first input voltage is 3.6 V, and the output voltages for boost, buck and boost-buck modes are 8 V, and 1.5 V, and 3.8 V respectively. The inductor value is equal to 22 μH . The first, second, and third output capacitors are 22, 32, and 100 μF , respectively. Here, the duty cycle is adjusted every 1 msec.

Fig. 11 shows outputs waveforms when the current drawn from the first output doubles. The first, second, and third output currents are equal to 10 mA, 5mA, and 40mA, respectively. The switching frequency for all three outputs is constant and equal to 5 kHz. The inductor current waveform and the waveforms of the output voltage can be seen in Fig. 12 for some periods. Also, phase shift is considered so that there is no overlap between the signals given to the switches.

In Fig. 13, the first, second, and third output currents are 5 mA, 1mA, and 40mA, respectively, and the current drawn from the first output doubles. The switching frequencies for the first, second, and third outputs are 1 kHz, 2.5 kHz, and 5 kHz, respectively. As can be seen, the first and second output voltage ripples are acceptable here. Because the currents drawn from the first and second outputs are less, the frequency is also reduced (Fig. 14).

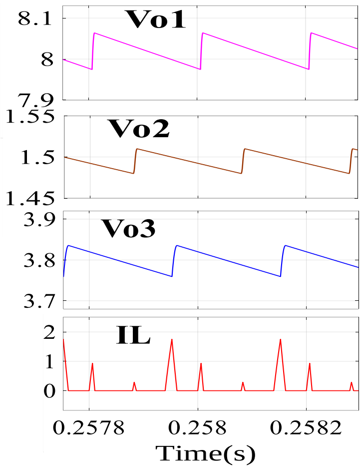

Fig. 12: Simulink simulation. (b) output voltages and inductor current in some periods. f_s = 5 kHz.

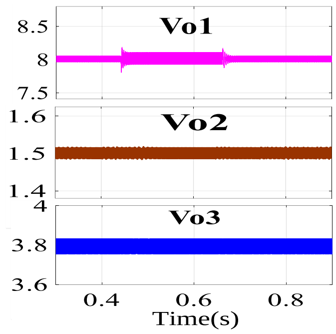

Fig. 13: Simulink simulation. output voltages. I_{o1} = 5 mA, I_{o2} = 1 mA, I_{o3} = 40 mA. f_{s1} = 2.5 kHz, f_{s2} = 1 kHz, and f_{s3} = 5kHz.

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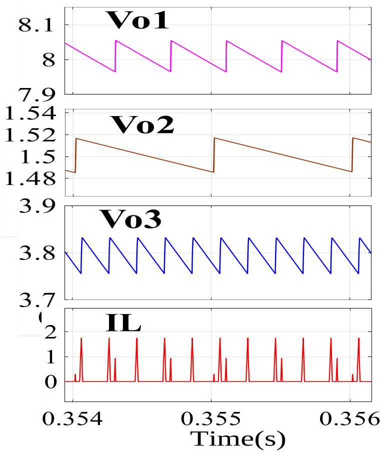

Fig. 14: Simulink simulation. (b) output voltages and inductor current in some periods. f_{s1} = 2.5 kHz, f_{s2} = 1 kHz, and f_{s3} = 5 kHz.

As mentioned, when the first input has a low energy level, the second input is used. We considered the input voltage variable, indicating that the system remains stable when the converter switches to the second input. Fig. 15 shows this test.

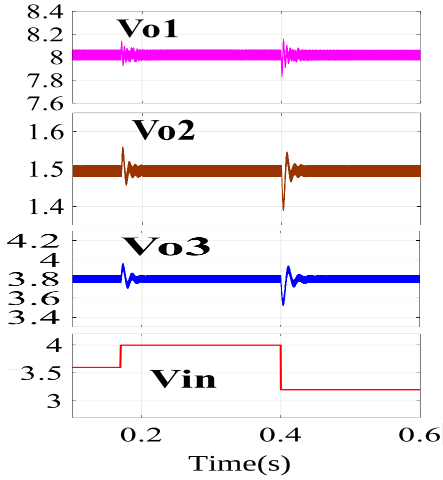

Fig. 15: Simulink simulation. output voltages with variable input.

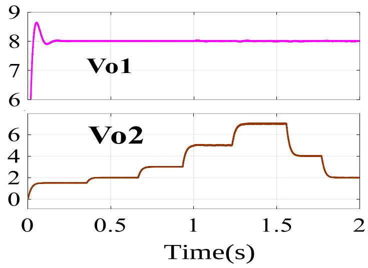

Fig. 16: Simulink simulation. output voltages with variable V_{ref2}.

TABLE 1: COMPARISONS WITH PREVIOUS WORKS

Reference	[1]	[2]	[3]	[4]	Proposed Converter
Conversion Method	Buck	Buck-Boost	Boost Buck Buck-Boost	Buck	Boost Buck Buck-Boost
Operating Mode	CCM	DCM	CCM	DCM	DCM
Max switching frequency	80 kHz	200 kHz	100 kHz	250 kHz	5 kHz
Inductor(μH)	100	4.7	500	4.7	22
Output capacitor(μF)	220	1, 10, 100	47	2.2	22, 32, 100
Controller	PSM+PFM	PSM	PWM	PFM	PWM

Also, the second output voltage is considered variable to show that this converter can work in three different modes (buck mode, buck-boost, and boost mode). As can be seen, the second output follows the relevant reference voltage (V_{ref2}) well (Fig. 16). And considering the appropriate phase shift both in this test and in previous tests, the problem of cross-regulation between outputs is very small.

To illustrate the key features of the proposed MISIMO converter further, a brief comparison between the proposed converter and the previously proposed converters is presented in Table I.

V. CONCLUSION

In this paper, a multi-input multi-output switching converter is designed with digital control to be used in energy harvesting applications. Sources for energy harvesting are connected to energy converters such as solar cells, wind turbines, thermoelectric generators, etc. Also, one of the inputs are connected to a battery. The output voltages are determined based on the requirements set by power consuming applications. An extra output is considered for charging the battery. Whenever energy sources have enough energy for harvesting, the converter uses those inputs to supply the outputs. When the harvested energy is more than enough, it is used for charging the battery, which will be later used at the times when the harvested energy is not sufficient, or the load current increases. Digital algorithms for determining the switching time of the switches are explained in the paper. Also, the algorithm for charging the battery is explained. Simulation results are performed in MATLAB to confirm the proper operation of the proposed algorithms.

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