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PID Controller for DC-DC converter under dynamic load change in photovoltaics based low-voltage DC microgrid

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Abstract
Today, DC Microgrid gain more attraction due to increasing electronic digital devices application such smart-phones, smart-tvs, and other digital apparatus which are operated in DC form. In the common grid, the electric power from AC source is converted to DC voltage for powering the digital devices as load. Hence, there are power conversions from AC-DC and potentially loss energy during conversions. DC Microgrid consisted of sources, loads, distribution lines and energy storages. In small capacity DC Microgrid, the stability of the system is vulnerable by dynamic load change. During load demands fluctuations, the DC Microgrid voltage is also dynamically fluctuated and can reach over the designated rate. To solve this problem, the PID controller is introduced in the DC-DC converter for maintaining the voltage rate at designated value regardless the load demands. In this paper, the DC Microgrid is consisted of photovoltaics as DC sources, XL-6019 as DC-DC converter, Arduino as controller, voltage and current sensors, distribution lines and loads. The proposed method is evaluated via experimental results. The responses of the proposed method in the DC Microgrid system are presented, evaluated, discussed, and compared between with and without applied method. The experimental results indicate that the proposed method has ability to reduce the voltage profile fluctuations during load demands changes and in short time.

1. Introduction

A Microgrid (MG) now gains more attraction and emerges a concept of the new electrical grid network [1], [2]. A MG is consisted of Distributed Generation (DG) units primary from renewable energy sources such photovoltaics (PVs), locally loads, Electrical Energy Storages (ESSs) and short distance distribution electrical network [3]–[5]. The most advantages of the MG are included significant reducing power loss during transmission lines, more independent adjusting the customer demands, faster recovery from natural disaster and technical issues, and more flexibility for integration among energy sources in the same electrical network [6], [7].

In addition, the fast developing of digital technology devices such phones, tvs, electric vehicles, etc. which operate in DC form instead of AC form, and world widely application of DC sources such PVs and Battery, introduce the discussion of the DC form as standard for the small and short line grid. By employing the DC form, the losses energy during conversion from DC to AC (e.g. PVs to grid) and AC to DC (e.g. grid to digital devices as loads) can be significantly reduced and eliminated [8]–[10].

The massive use and widely penetration of PVs especially in resident area, creates a small-electrical network as home based electrical network. In this case, the main controller of the PVs must be able to determine electrical sources available to be used whether from the grid, PVs power or ESSs [11]. Similar concept can be adapted for group of houses at the small and remote area, which rely on their own renewable energy sources for regulating voltage, current, power, and other designated factors. In PVs and ESSs based DC MG, the controller of the DG is performed by the DC-DC converter which convert from the source voltage level to the designated voltage of the DC MG system [12]. Maintaining the DC MG voltage at the designated level during loads fluctuation demands with unknown and fluctuation loads is the challenge the control of DC MG today [13], [14]. In DC MG, the fluctuations of the load demands have big influences on the system stability [15], [16].

Several studies investigate and discuss the droop-control technique in the DC MG. In this technique the fluctuation of the load demands is compensate by increasing voltage output of DC-DC converters [15], [17]. However, by increasing load capacity in the MG, the current flowing to the load is also increased, and thus the loss power during distribution lines is increased respectively. The increasing loss power is not compensated properly in this technique. On the other hand, the DC-DC converters capacities are different each other and are not able to control by this technique accordingly [18].

Many studies report the effect of the fast response of the DC-DC converters. Several techniques require fast output response of the DC-DC converters whilst others do not, according to their technique [19], [20] However, when such parameters i.e., rise-time, settling-time are not complied the requirements, the voltage oscillation of the grid will impose the instability of the system. Almost the published methods are to investigate and evaluate the DC MG via computer simulation, and thus those above discussed parameters are generated by an ideal DC-DC converter which has high linearity of the outputs. While in fact, linear output of the DC-DC converter is hard to be achieved. And hence, the outputs of the DC-DC converter are more often oscillated, and the stability of the DC MG is vulnerable [21], [22].

The proposed method in this paper is constructed and evaluated based on experimental of the DC MG. The DC MG is consisted of PVs as DC source, XL-6019 components as DC-DC converter, line distribution, impedance load, currents, and voltages sensors. The experimental can represent the real DC MG which is rare as Authors known in previous published papers. In addition, the load is fluctuated under circumstance condition with distribution impedances. Many published papers neglect the distribution lines and voltage drop, and those are the main contribution of this paper. In addition, the proposed PID controller is constructed under Arduino programming and data acquisition. And hence, the performance of the proposed method is evaluated based on non-ideal characteristics.

The contributions of the proposed methods are the proposed method are evaluated and tested under the real electronic components and experiments which are not in ideal parameters such in simulation, the distribution loads are counted and effects on the system performance such voltage drop are evaluated and compensated by the proposed method, and data acquisition performed based on the component clocks, therefore the proposed method can prove working on the data delay environment.

2. Research Method

The DC MG system in this paper is consisted of DC source, controller, DC-DC Converter, distribution line impedance and loads impedances, voltages, and currents sensors. The controller and DC-DC converter employed in this paper is Arduino and buck-boost converter of XL6019. The PID controller is performed by algorithm in the Arduino. The schematic of the experimental setup is described in Figure 1. The DC MG is powered by the PV and then maximized by Maximum Power Point Tracking (MPPT). In this paper, the PV and MPPT are not more discussed further. We assume that the PV and MPPT can provide suitable power for the DC MG system.

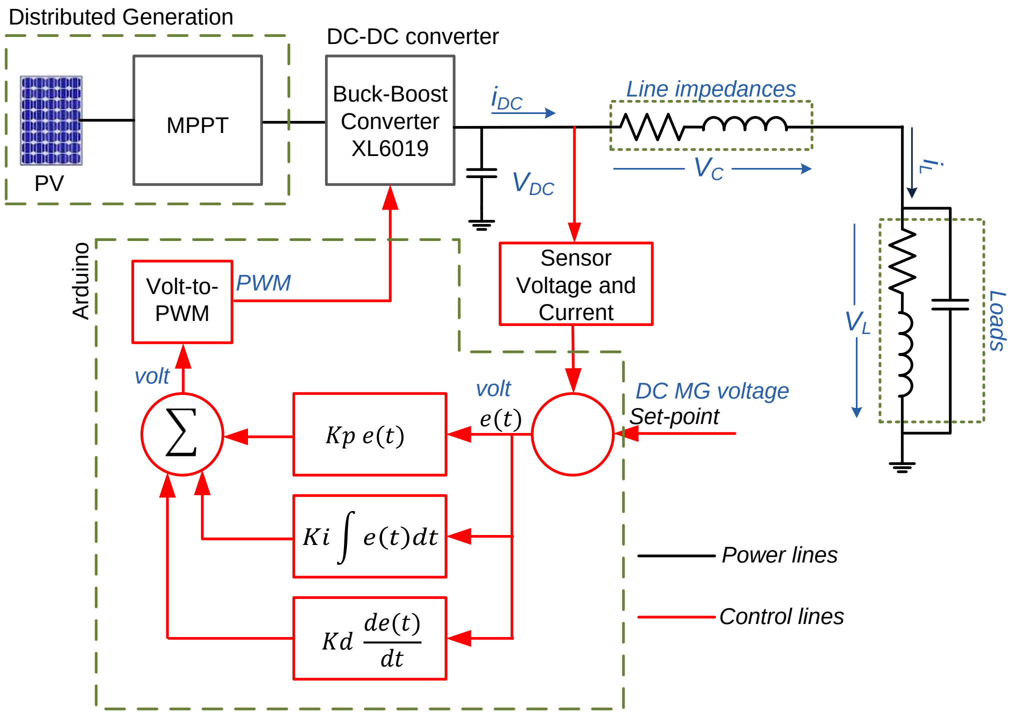

Figure 1. Schematic diagram of the experimental setup

In Figure 1, while the load demand is increased, the load current (i_L) is increased and load voltage (V_L) is dropped. By increasing i_L, the voltage droop in the line impedance (V_C) is increased, therefore the DC-DC converter output voltage (V_{DC}) should be adjusted to the new level for maintaining the DC MG common voltage at the designated level. These relationships can be expressed as Equation 1, Equation 2, and Equation 3.

$$V_{DC} = V_C + V_L \tag{1}$$

$$i_{DC} = \sum i_L \tag{2}$$

$$V_C = i_C Z_C \text{ and } V_L = i_L Z_L \tag{3}$$

Where Z_C, Z_L, i_{DC} and i_C is the line impedance, load impedance, DC-DC converter current output and line distribution current respectively. Substitute (3) to (1) and (2) can be obtained Equation 4.

$$V_{DC} = \sum (i_C Z_C + i_L Z_L) \tag{4}$$

However, the line impedances and load impedances are not practically to be measured and mostly unknown. They often are spread-out in geographical area. Therefore, directly implementation of the (4) is not possible due to unknown those parameters.

According to (4), the load demands fluctuations are influenced by changing of Z_L, and the value of Z_C is more relative fixed. Therefore, the (2) can be constructed with this assumption, and the load demands fluctuations (i.e. presented by i_L) by can be predicted by fluctuation of DC-DC converter current, as expressed as Equation 5.

$$\Delta i_{DC} \cong \sum i_L \tag{5}$$

The new level of DC MG voltage then can be estimated by the fluctuation of the Δi_{DC} compared with the previous level, which can be formulated as Equation 6.

$$\Delta V_{DC}\,(\%) \cong \Delta i_{DC}(\%)$$
$$\frac{V_{DC(t)} - V_{DC(t-1)}}{V_{DC(t-1)}} \cong \frac{i_{DC(t)} - i_{DC(t-1)}}{i_{DC(t-1)}} \tag{5}$$

Where the $V_{DC(t)}$ and $V_{DC(t-1)}$ is the new and previous set-point of the DC-DC converter respectively, as depicted in Figure 1. The (6) will be used as the proposed formula in this paper.

The Volt-to-PWM as shown in Figure 1 is the formula for converting the desired voltage to the PWM duty-cycle of the DC-DC converter. This conversion is required due to the output of the DC-DC converter is in voltage based, however the controller is based on PWM signal. The experimental results of the relationship between PWM duty-cycle with the DC-DC converter (i.e., buck-boost converter XL6019) is presented in Figure 2.

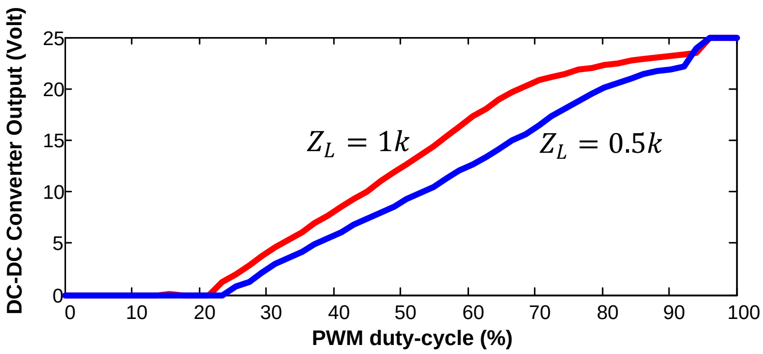

Figure 2. Relationship between DC-DC converter output and PWM duty-cycle with different load impedance.

Figure 2 shows that the DC-DC converter starts generating voltage output with around 22% of PWM duty-cycle and increased up to 25v maximum output level. According to Figure 2, the Volt-to-PWM (V_tP) relationship can be formulated as Equation 7.

$$V_tP = \frac{dc_{max} - dc_{min}}{out_{max} - out_{min}} \tag{5}$$

And V_tP = 3.12. To avoid infinity loops for obtaining the optimum parameters combinations, the parameters tuning of the PID controller are predicted by using Ziegler-Nichols second method, and are presented in Table I. These parameters will be used for the prediction of the optimum parameters as used by [23], [24]; however, adjustment is still required and then validated by experimental results which are discussed and presented on next section.

Table 1. Optimum Parameters of PID predicted by Ziegler-Nichols second method

Type of Controller	K_p	K_i	K_d
P	10	0	0
PI	9	0.108	0
PID	12	0.24	0.15

3. Result and Discussion

The proposed schematic as shown in Figure 1 is conducted via experiments in laboratory. Firstly, the optimum parameters of PID controller as presented in Table 1 are used and applied on the DC MG system [25]. The experiments are also performed by adjustment of those parameters, and the results are evaluated by comparing them with several indices included rise-time, overshoot, steady-state-error, and settling time. Secondly, the several possible optimum parameters according to those indices are employed in the DC MG system. In these experiments, the parameters are evaluated during fast load demands fluctuations which are presented by changing load impedances.

3.1 Steady-state load impedances

All the experiments are set-up with set-point of 12V as DC MG voltage rate and loads are set-up at the constant impedances. The first experiments are used the P controller with several parameters of *Kp*. The second and third experiments are performed using PI and PID controller. The responses of the DC MG system with P, PI and PID controllers are illustrated in Figure 3, Figure 4 and Figure 5 respectively. The results are analyzed according to designated indices and resumed in Table 2.

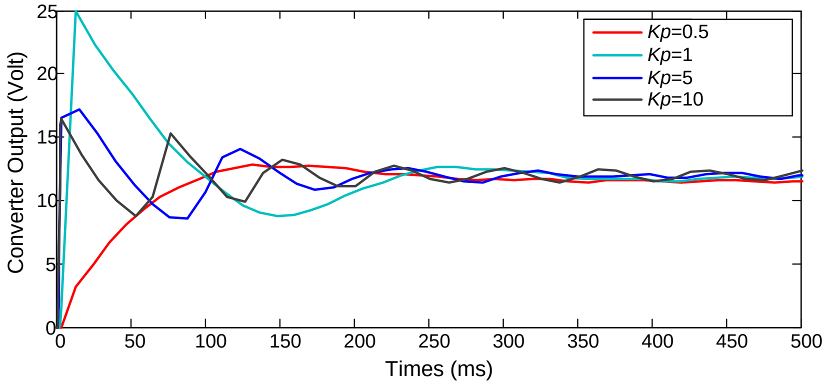

Figure 3. P Controller responses with different parameters

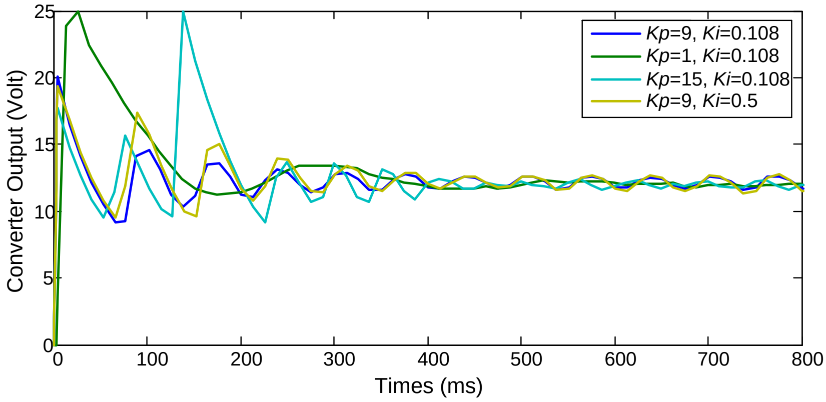

Figure 4. PI Controller responses with different parameters

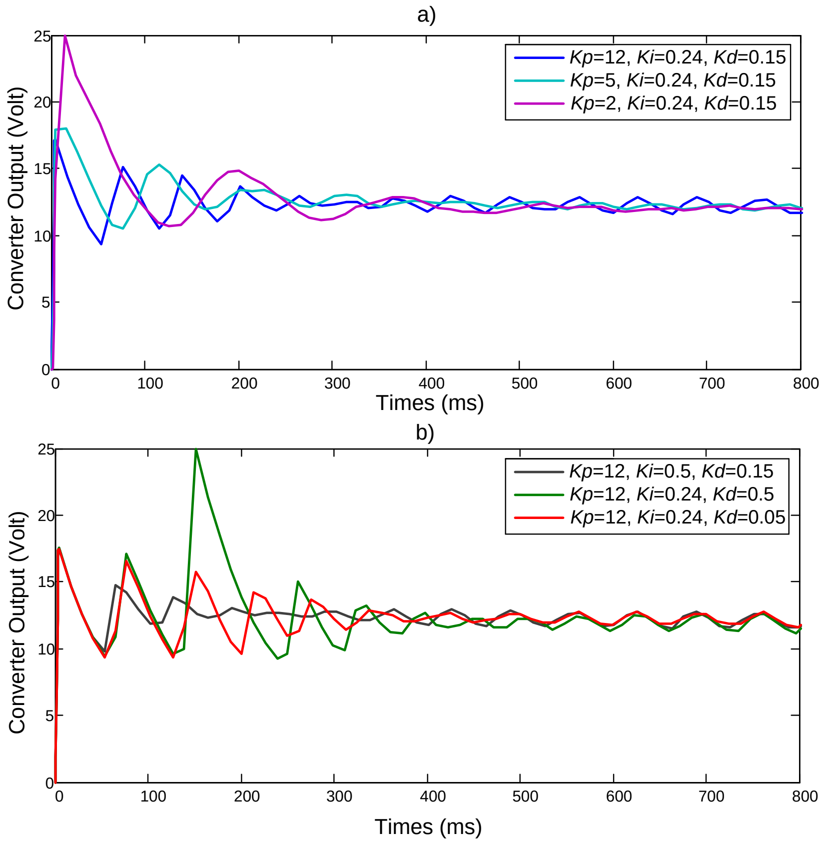

Figure 5. PID Controller responses with different parameters

Table 2. Performance evaluation of the PID controller parameters

K_p	K_i	K_d	Rise-time (ms)	Overshoot (%)	Steady-state error (%)	Settling time (ms)
0.5			96	6.92	5.08	445
1			13	108.3	3.08	602
5			3	43.58	2.08	553
10			3	37.08	4.5	626
9	0.108		3	67.42	4.5	450
1	0.108		13	108.33	1.25	677
15	0.108		3	108.33	3.25	622
9	0.5		3	61.08	5.50	723
12	0.24	0.15	3	43	5.67	610
5	0.24	0.15	3	49.92	2.25	653
2	0.24	0.15	4	108.33	1.67	624
12	0.5	0.15	3	46	5.25	453
12	0.24	0.5	3	108.33	5.25	667
12	0.24	0.05	3	45.58	5.50	580

According to experimental results in Table 2, we can assume and choose the suitable controller for the specific characteristic of the DC MG. When a faster response is required due to fast load demand fluctuations, then the smaller rise-time can be chosen, however while a DC MG requires a stable voltage level on the grid, the combination of lower steady-state-error and settling-time can be selected. In several cases, the maximum level of the DC MG is critical (e.g., 10%), the parameter of overshoot should be considered.

3.2 Dynamic load impedances

For evaluation purpose, the responses of the DC MG system with several parameters in Table 2 are compared with the without any proposed controller applied. On these experiments, to obtain the DC MG stability response, the proposed methods are evaluated during the load demands fluctuations at every 1s. The Figure 6 shows the voltage profiles on the DC MG when load demands fluctuations are at *t* = 1s, *t* = 2s, *t* = 3s, and *t* = 4s without the proposed method and with P, PI and PID controller.

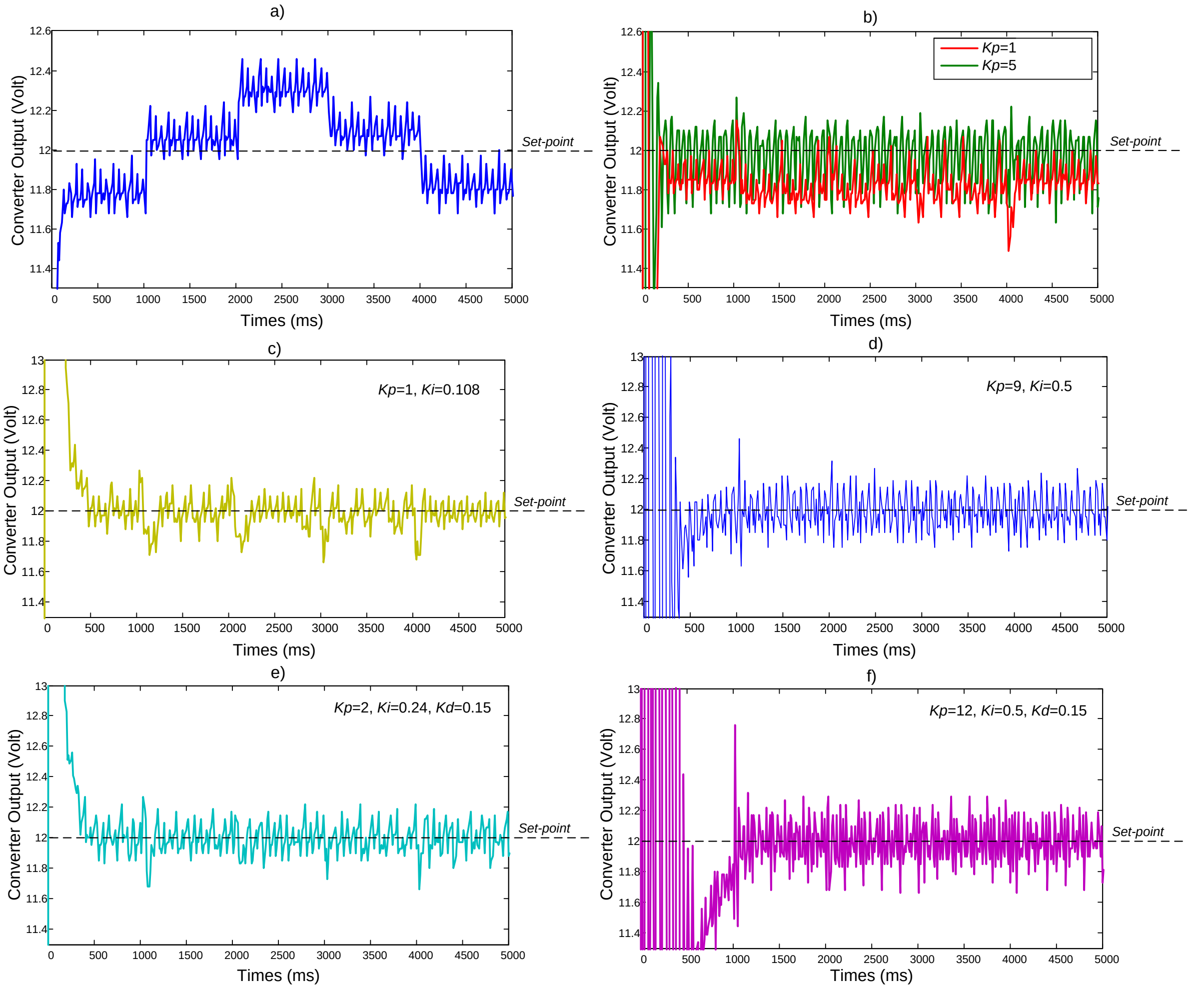

Figure 6. Voltage profiles of DC MG during load fluctuations: a). without any method, b). with P controller, c) and d). with PI controller, and e) and f). with PID controller

Figure 6 a) shows that without the proposed method, the voltage in the DC MG is fluctuated and influenced by the load demands. The DC MG voltage raised up to 12.4 volt when the load demand is decreased and dropped up to 11.8 volt when the load demand is increased. The DC MG voltage profiles are higher than maximum acceptable limit i.e., 10% from the designated 12-volt level. By applying P controller with *Kp*=1, the DC MG voltage can be maintained during load fluctuations. However, the DC MG voltage is lower than designated rated which are maintained at 11.8 volt. On the other hand, by *Kp*=5, the DC MG voltage can be maintaned at around designated rate during load fluctuations as depicted in Figure 6 b).

Similar results are also be proved in Figures 6 c), d), e) and f) where the proposed method with *Kp*=1 *Ki*=0.108, *Kp*=9 *Ki*=0.5, *Kp*=12 *Ki*=0.24, *Kd*=0.15 and *Kp*=12 *Ki*=0.5, *Kd*=0.15 is applied, respectively. With the proposed method, the DC MG voltage can be maintained at the designated rated regardless the load fluctuations. The results also indicate that the proposed method has capability to reduce the load fluctuation in short time. The DC MG voltage can be healed in less than 1s of processing time.

4. Conclusion

The aim of this paper is to propose and evaluate the P, PI and PID controller for the voltage regulation of DC MG during load demands fluctuations. Without any proposed methods, the voltage profile of the DC MG is fluctuated following the load demands fluctuations. However, by implementation of the proposed method the voltage of DC MG can be maintained at designated rate regardless the load impedances and fluctuations. The results are also indicated that the proposed methods have ability to response the system in short time.

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