Load Sharing by Decentralized Control in an Islanded Inverter-based Microgrid using Frequency Tracking

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Abstract
Microgrids have been defined as an efficient and practical concept to cover flaws in traditional power system related to system expansion and renewable energy utilization. By increasing demand energy, the need to generate more electric power is raised. However, the distance between generation centers and consumption centers causes more energy loss in power system and power system expansion is considered costly and to some extent infeasible. In addition, nowadays using renewable energies such as wind energy is inevitable, as a result using power electronic mediums is necessary. Microgrids are mostly preferable because of the ability to perform in islanded mode. In order to have stable-islanded Microgrid, electric loads inside the network should be shared on Voltage Source Converters respect to their nominal capacity. Droop control has been known as a method to share loads in decentralized way, although it has shortcomings. In this paper by introducing novel method named Frequency Tracking and applying that on droop control system, electric loads inside an islanded Microgrid are shared on generation units properly with fast and acceptable dynamics and droop control system is modified. Simulation results in PSCAD are confirmation of proposed system to have stable islanded Microgrid.

Keywords: Decentralized Control, Frequency Tracking (FT), Load Sharing, Microgrid, Voltage Source Converters

1. Introduction
In last decades, using Renewable Energies and Distributed Generations (DG) has become inevitable. Regarding the economic and technical benefits of Distributed Energy Resources (DER), Microgrids are known as a practical and useful solution for the realization in advantages of distributed energy resources. Microgrids are introduced as small size networks, contain variety of electrical and heat loads and distributed electrical energy resources, including renewable energies. One of the main advantages of distributed generation is providing energy generation units close to the energy consumption and thus reduction the loss of energy. DG assistance services also include the provision of reactive power means and providing reservation services and saving energy. These issues have been the subject of many studies in recent years. Other advantages of using distributed energy resources is reduction the environmental impacts of electrical energy generation and decrease utilization of fossil fuels. From the perspective of power system, Microgrid is a controllable cellular network and from the perspective of users it is a system with high reliability, low losses and high efficiency of energy production.

In Microgrids, increasing number of energy sources with lower capacity and energy storage devices that are connected to the grid through power electronic converters has created new control issues in mentioned networks. In these networks, energy sources connected to the network, whether DGs or distributed energy storage systems have the ability to increase or decrease output power without having large impact on the stability of Microgrid.

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One of the preferred power electronic interfaces used in Microgrids is Voltage Source Converter (VSC). In context of controlling Voltage Source Converters that can guarantee correct operation of Microgrids, materials in\textsuperscript{12} and\textsuperscript{13} are presented. Mentioned methods are based on the output voltage phase and amplitude control of converters.

For Microgrid operation, two major modes are defined, stiff power system-connected mode and islanded mode\textsuperscript{14}. In stiff power system-connected mode (Grid-Connected), distributed generations inside Microgrid follow the grid parameters, and the injection of energy into the network is collated with defined variables of bulk power system (frequency and voltage). This operation mode of power electronic converters in Microgrid is known as current control strategy\textsuperscript{15}. However, because of the ability of Microgrids to perform autonomous or islanded, many attractions have been absorbed. In islanded Microgrid, stabilizing grid voltage and frequency is VSCs' duty. Several methods have been proposed for centralized and decentralized control of islanded Microgrid\textsuperscript{16}. The impacts of communication lines between converters and control method advantages and disadvantages can be found in\textsuperscript{17}. Control of Distributed Energy Resources in an islanded Microgrid is more difficult than conventional power system. This is due to distance of distributed energy resources, fast dynamics and small time constant of energy generation units, the unbalanced nature of Microgrids, low energy storage capacity, lack of inertia in network and high level uncertainty in Microgrid structure that can be a significant factor introduced in\textsuperscript{18}.

One of the important issues of stability in islanded Microgrid including power electronic converters is sharing load over energy resources which are discussed in details in the next section. In islanded Microgrid, voltage source converters, in addition to load sharing, are responsible of regulating voltage and frequency characteristics of whole network and use local feedback to monitor their own performance\textsuperscript{19}. In this paper, by using a new method, electrical loads are shared on distributed resources respect to their capacity in islanded Microgrid by decentralized control. The goal of this study is presenting a control system for an islanded Microgrid, without depending on Microgrid configuration and parameters that can stabilize Microgrid operation and have fast dynamic for voltage source converters. The proposed method is based on tracking frequency of a unit as Master or reference in Microgrid and applying droop control in the system simultaneously. Therefore, the method is named Frequency Tracking (FT).

In ongoing parts and in the second section of this article, we discuss load sharing. In the third section, proposed method has been discussed, including the related control and mathematical equations. In the fourth section, under study networks have been simulated. The outcomes of the implementation FT were presented beside and the last section is devoted to summarizing the contents and conclusion.

### 2. Load Sharing

In traditional networks, generation units are relatively large, and due to rotation of turbine and synchronous generator, frequency of each unit is readable and great inertia exists for controlling network. These features help facilitate compensation of additional or lack of power by distributing power among units\textsuperscript{20}. In an inverter-based Microgrid, distributed power resources have been connected to the grid through power electronic interfaces. Therefore, in the absence of inertia in the network for stable operation, it is not possible to act as synchronous machines in conventional power systems. In an islanded Microgrid all of the DGs are responsible for keeping network voltage and frequency within the acceptable range. Because of the low relative capacity of DGs in islanded Microgrid, keeping balance in power generation and consumption is very important and several researches have addressed this issue\textsuperscript{21–22}. DGs in islanded Microgrid should share network loads based on their capacity and circulating current between energy resources must be avoided\textsuperscript{23}. In conventional power systems, any imbalances in the generation of active power lead to frequency change. As a result, balancing the output active power of each generator will be determined by frequency difference between reference frequency and governor frequency droop characteristic. But in Microgrids including power electronic converters without presence of synchronous generators, a conventional approach with measuring differences in rotational frequency will not be feasible\textsuperscript{24}.

In order to share loads on power electronic units, droop control method of active Power/Frequency (P/F) for implementation of a similar structure to conventional power systems is presented\textsuperscript{1}. Also for the control and stabilization of system voltage and reactive power sharing among units, droop control of reactive power/voltage (Q/V) has been named as a practical solution\textsuperscript{12}. In other words, the characteristic of drop in P/F will be a normal relation with frequency and active power and characteristic of drop in Q/V links voltage and reactive power. In some references this issue has been discussed that the
droop control in P/F and Q/V is only feasible in networks with dominant inductive lines and due to resistive characteristic of Microgrids active power/voltage (P/V) droop is used. Figure 1 shows the general characteristics of voltage and frequency variations versus changes in active and reactive power. Complete set of droop control equations and terms to share loads on voltage source converters can be found in reference. In this paper we present a novel method, in addition to eliminating droop control sensitivity to structure of communication lines and networks, active power required for Microgrid, accurately and with fast and reliable dynamics will be shared among electric power generation units. It should be noted that the main focus is concentrating on sharing active power for supplying local loads that is the main operation of Microgrids.

For better recognition of sharing loads on sources and relation between active power and frequency, firstly, it is necessary to consider a simple network composes of a common load and two VSCs units. Figure 2 shows an instance of the network structure. In Figure 2, each VSC unit according to its rated capacity supplies load.

For applying droop control in VSCs at first we introduce main equation in this regard:

\[ f' = f_n + K_{pi} \left( P_n - P_{si} \right) \]  

In equation (1), \( f_n \) is the nominal frequency at the nominal power \( P_n \). \( K_{pi} \) and \( P_{si} \) are the active power droop coefficients and output active power of the VSCs respectively. It should be noted that \( K_{pi} \) is a small and positive number and is proportional to the nominal capacity of the unit. Active and reactive power droop coefficients in VSCs determined regarding to the changes in the values of frequency and voltage. Equation (2) shows \( K_{pi} \) calculation regarding to these changes.

\[ K_{pi} = \frac{\Delta f}{\Delta P_{si Max}} \]  

In order to have dynamic analysis of mentioned equations and the need for droop coefficient to have stable network in load sharing, reference has stated important dynamic equations. In summary, despite the fact that droop control causes frequency to differ from its nominal value, it eliminates the VSC signal communication lines and it can be used in load sharing.

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3. Proposed Frequency Tracking Method (FT) in Load Sharing

Before addressing the mathematical equations governing structure of the FT, we refer to the network Figure 2. Assuming that two VSCs have different nominal capacities and converter number one is known as Master and the other as Slave, we implement conventional droop control system (Figure 3).

In the control system shown in Figure 3:

- $K_{fp1}$: Droop coefficient determined for the Master unit;
- $P_1$: Generated power by considered Unit;
- $P_{1n}$: Nominal power of first unit in per unit;
- $f_n$: Nominal network frequency;
- $f_1$: Generated frequency of the Master unit.

In other words, first VSC unit, generate nominal power with nominal frequency (50HZ). In FT method, other units are required to track generated frequency of the Master Unit. Therefore, structure of control system should satisfy it. For this purpose, a PI controller in control loop of the second converter has eliminated the frequency error between two units. Figure 4 shows the general form of PI control system.

In Figure 4, variables are defined as follows:

- $f_1$: Generated frequency by Master unit after implementation of droop control;
- $f_b$: Frequency set for Slave unit after implementation of droop control;
- $f_2$: Output Frequency ordered to second unit or Slave.

As mentioned in previous parts, it is necessary to have common frequency in whole network in order to stabilize it. In Microgrids including VSCs, owing to have decentralized control, frequency and generated power of each unit cannot be set by signal commands. Therefore, a control method should be presented that in addition to stabilize frequency, control Microgrid in a decentralized way and during stable operation, loads inside network should be shared accurately. Figure 5 shows the FT performance for the second unit.

In the proposed method to have fixed frequency in the network, output frequency of each unit should be as same as frequency of master unit. This is done by a PI controller. The PI controller change frequency of units and set frequency difference to zero. In ongoing sections we consider this method and its advantages.

According to Equation 1 and control structure of FT, Equation (3) can be determined as the output frequency of second unit that is measured on the terminal as defined below:

$$f_b = f_n + K_{fp2} \left( P_{n2} - P_{o2} \right)$$

(3)
According to the block diagram of Figure 4, equation (4) shows output frequency of second unit according to changes in the frequency of the first unit and frequency generated by droop characteristic in the second unit:

\[
f_2(s) = \frac{k_p + \frac{k_i}{s}}{1 + k_p + \frac{k_i}{s}} \times f_1(s) + \frac{1}{1 + k_p + \frac{k_i}{s}} \times f_b(s)
\]  

(4)

In equation (4), the values of \(k_p\) and \(k_i\) are proportional and integrator coefficients of PI controller respectively.

According to Equation (4), the proposed control system has a pole on the left side of the imaginary axis. As a result, the first order system prevents instability and fluctuating at the moment of load changing. Eigen values of the control system can be calculated by equation (5):

\[
\dot{\lambda} = -\frac{k_i}{1 + k_p}
\]  

(5)

Therefore, Integrator in control system for stabilizing Microgrid is necessary when changes occur.

To better introduce of the transfer function, we rewrite equation (4) as equation (6).

\[
f_2(s) = \frac{k_p + \frac{k_i}{s}}{1 + k_p + \frac{k_i}{s}} \times (f_n + k_{fp1P_o1}) - \frac{k_p + \frac{k_i}{s}}{1 + k_p + \frac{k_i}{s}} \times (k_{fp2P_o2}(s))
\]  

\[
+ \frac{1}{1 + k_p + \frac{k_i}{s}} \times (f_n + k_{fp2P_o2}) - \frac{1}{1 + k_p + \frac{k_i}{s}} \times (k_{fp2P_o2}(s))
\]  

(6)

In equation (6), the generated frequency signal by the second unit for \(P_{o1}\) and \(P_{o2}\) as input signals for control system is shown.

In the system that consists of two units, total requested active power in network is sum of each unit’s active power, as a result:

\[
P_l = P_{o1} + P_{o2}
\]  

(7)

So with substitution of equation (7) in equation (6), the frequency change in unit 2 for load changes in the network and unit 1, can be calculated as equation 8.

\[
f_2(s) = \frac{k_p + \frac{k_i}{s}}{1 + k_p + \frac{k_i}{s}} \times (f_n + k_{fp1P_o1}) - \frac{k_p + \frac{k_i}{s}}{1 + k_p + \frac{k_i}{s}} \times (f_n + k_{fp2P_o2})
\]

\[
\times (k_{fp1P_o1}(s)) + \frac{1}{1 + k_p + \frac{k_i}{s}} \times (f_n + k_{fp2P_o2})
\]

\[
- \frac{1}{1 + k_p + \frac{k_i}{s}} \times (k_{fp2}(P_l(s) - P_{o1}(s)))
\]  

(8)

For better illustration of power changes in network we use step function. As a result, the entire network power suddenly will alter from \(P_{o1}\) to \(P_{o2}\). Generated power by the first unit according to the droop characteristic will change as step. Step change in active power demanded by the grid and the first unit generated power in \(s\) space are shown in equations (9) and (10).

\[
P_l(s) = \frac{\Delta P_l}{s}
\]  

(9)

\[
P_{o1}(s) = \frac{\Delta P_{o1}}{s}
\]  

(10)
Changes in steady-state output frequency of the second unit are calculated according to equation (11).

\[ \Delta f_2(t) = -\left( k_{fp1} \times \Delta P_{o1} \right) \]  \hspace{1cm} (11)

If we look at equation (11), the first term on the right represents the frequency change in the Master unit. So the frequency changes in the proposed control system in the second unit, is fully compatible with master unit and no frequency difference in stable operation of the network will exist.

However, in steady state, for the second unit \( f_o \) with \( f_2 \) and both with \( f_1 \) will have same value. Thus according to the equation (2):

\[ \Delta f_2(t) = -\left( k_{fp2} \times \Delta P_{o2} \right) \]  \hspace{1cm} (12)

If we consider equations (11) and (12), proved to result in:

\[ (k_{fp2} \times \Delta P_{o2}) = (k_{fp1} \times \Delta P_{o1}) \]  \hspace{1cm} (13)

Thus:

\[ \frac{k_{fp1}}{k_{fp2}} = \frac{\Delta P_{o2}}{\Delta P_{o1}} \]  \hspace{1cm} (14)

Equation (14) is the provision of load sharing on units using droop control which has been addressed in many references similarly\(^\text{[28-30]}\).

4. Simulation Results

To apply FT on a Microgrid and derive results, two different networks have been used. The first network is known as a standard network and has the same structure as in Figure 2. After extracting desired results, we will apply FT control system on a network with wider dimensions that includes five VSCs with dominant resistive asymmetric lines.

4.1 Network Under Study No. 1

In Figure 6, the network consists of two VSCs and communication lines that are dominantly resistive and also with centralized loads. Each VSC is connected to the network via an Inductor (\( L_1 \) and \( L_2 \)). In this form, line inductance in distribution system has not been disregarded. In table 3 (Appendix 1) values of variables and parameters associated with the network in Figure 6, is presented.

VSCs in Figure 6 are controllable converters that frequency and voltage control signals, via defined controller for each unit are injected. Also, the network consists of a fixed load with predefined values of active and reactive power as well as a variable load in order to change the operating point during stable performance in the Microgrid. It is assumed that power generation units, have ability to generate nominal determined voltage. Therefore, the control system acts only on frequency and shared active power. Inductors \( L_1 \) and \( L_2 \) are larger than the inductors of lines. In order to create asymmetric structure in the network, the Inductors are considered non-equal.
Nominal power of the unit number two (Slave) is half of the nominal power of the unit number one (Master). Therefore, we expect one third of the total power to be provided by this unit in load sharing. Also the droop coefficient for unit one is 0.012, so according to equation (15), to have acceptable load sharing among units, the second unit droop coefficient must be determined 0.024. Fixed and variable load values in 1 MVA base have been shown in Table 4 that on this operating point they designated for operation close to their nominal values and, at the end, network rated voltage and frequency, have been selected, 20KV and 50HZ, respectively. In operating the network, it is assumed that the constant load is always connected to network, but variable load once connected to network for five seconds and then removed. In fact, we tried to impose changes to the network to discuss the dynamic of changing power and accuracy of load sharing in the asymmetrical conditions.

Figure 7 shows simulation result using proposed control system. In this figure power generated by each unit for load sharing in the islanded mode and decentralized control has been presented.

As expected, the active power generated by the second unit is precisely half of the active power generated by the first unit. In addition, both units have an acceptable dynamics in load sharing. Overshoot and undershoot
values of second unit can be adjusted by changing coefficients of PI controller and make them desired values.

Figure 7 shows active power sharing in changing load, this sharing is done by controlling frequency of each unit with respect to the droop characteristic. Thus, in Figure 8 we can see instant frequency of units simultaneously.

According to Figure 8, the frequency of second unit tracks frequency of first unit, confirming validity of the proposed control method. Network frequency at the time of entering variable load in the network will drop about 0.003 Hertz that is negligible. The decline in the frequency depends on the droop coefficient of system control in units. As the droop coefficient is smaller, lower frequency drop can be seen but the dynamic of the shared power would be slower and in some cases would be unacceptable.

4.2 Network Under Study No. 2

In order to create more asymmetric profile approaching to study characteristics of a real system, the network shown in Figure 6 has been expanded and network, illustrated in Figure 9, is introduced.

Similar to standard model in Figure 6, in addition to local loads, network loads in Figure 9 are divided into two parts. First part is the load connected to network permanently and the second part is the variable load that at a certain time is connected to network and then removed when needed. The purpose of using variable load is showing performance of the proposed control system when power demanded by Microgrid changes.

Among the items, stability and quick dynamic and acceptable load sharing on each unit according to the nominal capacity of that should be considered during load sharing.
According to set values for elements in the network that have been mentioned in Appendix Table 2, as observed, capacity of units are different but total capacity of the network has been determined about 2.3 MW. It should be noted that it is assumed the Microgrid is able to supply more than the nominal capacity in short duration. After identifying the under-study Microgrid to evaluate the performance of control system development, we discuss simulation results and see that everything like the number and the location of sources and loads are not determinant for control system and according to the droop characteristic, load will be shared among units accurately.

### 4.3 Normal Operation of the Network

Figure 10 shows the simulation results for generated power by each unit.

Figure 10 indicates that the net active power is shared among the Microgrid according to the nominal capacity of each unit. As shown in Appendix 2, the first unit has the most nominal capacity and the fifth unit has the lowest capacity. On the other hand, by focusing on the figure 10, we can even see the slightest changes in network happens to the large units and the units with small capacity will see changes more than others, therefore, for the fifth unit, by sudden changes in load, overshoot and under-shoot are observed.

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**Table 1.** Operating Points in Expanded Microgrid in The 8th Second

| t=7th sec | t=9th sec |
|-----------|-----------|
| Before removal of third unit | After removal of third unit |
| \( f_{1(7)} \) | 49.9911 | \( f_{1(9)} \) | 49.9911 |
| \( P_{1(7)} \) | 0.2819 | \( P_{1(9)} \) | 0.2819 |
| \( P_{2(7)} \) | 0.5518 | \( P_{2(9)} \) | 0.5518 |

**Table 2.** The operating point of network before and after third unit outage

| t=9th sec | t=7th sec |
|-----------|-----------|
| After removal of third unit | Before removal of third unit |
| \( P_{1(9)} \) | 0.8997 | \( P_{1(7)} \) | 0.7327 |
| \( P_{2(9)} \) | 0.3427 | \( P_{2(7)} \) | 0.2824 |
| \( P_{3(9)} \) | 0 | \( P_{3(7)} \) | 0.3774 |
| \( P_{4(9)} \) | 0.6703 | \( P_{4(7)} \) | 0.5523 |
| \( P_{5(9)} \) | 0.2324 | \( P_{5(7)} \) | 0.1918 |

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**Appendix 1**

**Table 3.** Value of Parameters Used in Figure 6

| Line 1(\( \Omega \)): 1+0.0942 j | \( L_1 \): 0.001 H |
| Line 2(\( \Omega \)): 1.1+0.157 j | \( L_2 \): 0.0015 H |
| \( P_{in} \): 0.8 MW | \( K_{L1} \): 0.012 |
| \( P_{in} \): 0.4 MW | \( K_{L2} \): 0.024 |
| \( V_{in} \): 50 Hz |

**Appendix 2**

**Table 4.** Value of Parameters Used in Figure 9

| Line 1(\( \Omega \)): 1+0.0942 j | \( L_1 \): 0.001 H |
| Line 2(\( \Omega \)): 1.1+0.2512 j | \( L_2 \): 0.0015 H |
| Line 3(\( \Omega \)): 0.8+0.0628 j | \( L_3 \): 0.0012 H |
| Line 4(\( \Omega \)): 1+0.1256 j | \( L_4 \): 0.002 H |
| Line 5(\( \Omega \)): 1+0.157 j | \( L_5 \): 0.001 H |
| Line 6(\( \Omega \)): 1.2+0.157 j |
| \( P_{in} \): 0.8 MW | \( K_{L1} \): 0.012 |
| \( P_{in} \): 0.3 MW | \( K_{L2} \): 0.032 |
| \( P_{in} \): 0.4 MW | \( K_{L3} \): 0.024 |
| \( P_{in} \): 0.2 MW | \( K_{L4} \): 0.018 |
| \( P_{in} \): 0.8 MW | \( K_{L5} \): 0.048 |
| \( V_{in} \): 20 kV |

| Local load 1: 0.01 MW | Local load 3: 0.008 MW |
| Local load 2: 0.009 MW | Local load 4: 0.01 MW |

| constant load (MVA): 1.6+0.1 j | \( f_{in} \): 50 Hz |
| Variable load (MVA): 0.5+0.01 j | \( V_{in} \): 20 kV |
Figure 11 shows Frequency of VSCs in the Microgrid in mentioned conditions and in the presence of load changes.

In Figure 11, the network frequency changes according to the conditions of exploitation listed in table 4 (Appendix 2). Output frequency of each unit individually has been shown and it is seen that all units, using the proposed control system, have the same frequency in the steady-state operation of the network.

Table 1 shows the operation point of generation units inside Microgrid according to operation condition set in Appendix 2, in the eighth second.

4.4 Withdrawal of VSC No. 3 from Network

Another aspect of analyzing proposed control system in stabilizing and load sharing in the network, is losing one unit due to the shutdown or interruption of the communication line with the other parts of the system. So in this part for analyzing control system in losing one generation part, we cut out the third unit from the network in stable operation mode and analyze stability and load sharing in the network after that.

Figure 12 shows generated power of VSCs before and after removal of the third unit from network.

It is assumed that generating power of third unit in 8th second suddenly comes to zero. According to Figure 12, after losing third unit, rest of the units share extra power. It should be noted that in this case in order to have better analyze on concepts, possibility to cross generated power by VSC units from nominal capacity is considered.

According to the results from figure 12, it can be mentioned that in the controlled Microgrid with proposed method, any disturbance in the network that consists line or generation outage, the stability of network would not be affected and normal operation continues. However, as noted before, Microgrid generation capacity must exist; otherwise the protective devices shed lower priority loads by load shedding.

To complete the discussion, Figure 13 shows output frequency before and after third unit outage during the Microgrid stable operation.

Figure 13 shows stability of grid at outage of one unit from network. As mentioned in the previous parts, it is necessary to have common frequency in generation units inside Microgrid that it would be liable in case of losing of one or more units.

Table 2 shows operating point of the network before and after third unit outage.

In simulation results for the standard model of the Microgrid and expanded model of this network, we can see that proposed control system has acceptable and better function in stabilizing the systems when load changes or one or several units stop working.

Load sharing of network loads among units, that are the first priority, is determined by the droop coefficient for the Master Unit that is accurately implemented.

5. Conclusion

In this paper we introduce a new control method for stabilizing a Microgrid and sharing loads on VSCs that results are acting to improve the performance of distributed energy resources in a Microgrid. The new method, called FT makes stable operation of network feasible by eliminating error between frequencies of the electric power generation units.

On the other side, load sharing is done using droop control that is proportional with each unit capacity and by this approach maximum utilization of the Microgrid generation units is achievable.

Advantages of proposed control method can be sited following: Microgrid high-speed stabilizing frequency in order to have stable network, proportional load sharing among units according to their capacity, high-speed response in load sharing, no sensitivity of the control system to the communication lines and the capability of adding and subtracting units without changing Microgrid control structure.

Addition to these, proposed control system has ability to adding new control variables, constraints and parameters to the system such as protective parameters and Economical power functions.

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