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Impact of Load Shedding on Frequency and Voltage System

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***Abstract* — System ability to continuously supply load is very important. One of the factors that influence that system ability is frequency and voltage stability. Frequency and voltage stability need to be considered during electrical power planning and operating to avoid system instability that can cause system blackout. Load shedding need to be done to restore the system into normal condition after interference or system instability. This research discusses impact of load shedding on frequency and voltage system.**

Keywords - Frequency Stability; Voltage Stability; Load Shedding; Impact of Load Shedding.

I. INTRODUCTION

Reliability, quality and stability are requirements for an electrical power system to be said as a good system. System must be able to continuously give electrical power supply with frequency and voltage value that is suited with regulation and must be able to return to the normal condition during disturbance.

Several conditions that cause the changing of frequency are short circuit disturbance, generator loss, sudden load changing etc. Varied load changing influence system stability. If required power more than power that was generated by generator, then those generator's frequency will be decrease. That condition not only influence frequency but also voltage [1]. Frequency and voltage stability greatly influence system stability.

Continuous frequency and voltage's decrease [1] can cause system total blackout. Therefore, further action need to be done so that system frequency back to stable condition at allowed level. Load shedding is one of the actions that must be done to solve those frequency and voltage decrease.

Load shedding have several method to release load gradually until system frequency and voltage return into normal condition or to determine which part of load that must be released. One of load shedding method is PV and QV Curve method.

This research will discuss impact of load shedding on frequency and voltage system. The simulation was done using ETAP (*Electrical Transient Analyzer Program*) Power Station to know whether system stability back to normal or not after load shedding during disturbance.

From the simulation of this research is expected to have an operator picture that will be done when there is instability in the system, and release the load in accordance with the calculation results to restore the system back to normal conditions.

II. METODOLOGY

A. Electrical Power System Stability

Electrical power system stability is electrical power system ability to return into balance condition after disturbance [2]. In operation of power system at any time there will be a change of capacity and load. That changing caused generator must adjust its capacity to supply load power changing through governor and excitation control. If it is not done, then system power balance will be disrupted. The Power balance between generator and load is one of the stability measures of electrical power system.

1) Frequency stability

Frequency stability refers to power system ability to maintain a stable frequency when there is imbalance between generator and load [2].

2) Voltage stability

Voltage stability refers to power system ability to maintain stable voltage at every bus after disturbance [2].

B. Load Shedding

Load shedding is an effort to prevent system instability. This instability will cause frequency and voltage's decrease and system phase angle instability. Those instabilities due to load increasing, the loss of transmission channel, the failure of generator and other components [3-5].

Load shedding is an ability to change the amount of power that is consumed by certain load bus [6].

Loss generator can be happened because of disturbance at generator that cause generator must stop operate. This will cause generator capacity decrease and not enough to supply required load from all the customer or supply varied load, which mean that at the certain time, load will be on peak position, and at the other time, load will be on normal position. When load on peak position, generator can not supply those load so that cause system instability.

System load has to be released immediately when system not stable. This must be done to prevent total blackout [5]. Beside that, system recovery will need many days.

C. PV and QV Analysis

There are several loads shedding method [4-5]. This research will use PV and QV Analysis.

1) PV analysis

PV Analysis is the connection between active power (P) and voltage (V). In this analysis, there are the lack of power and voltage in several critical busses [1,7] when the system experience disturbance that cause frequency deviation or voltage changing or both.

The amount of disturbance can be calculated from swing equation, where in this equation there are the rate of change of frequency and voltage changing [8]. This calculation will determine the amount of load that will be released. The different between generated power and loaded power should be calculated as follows:

$$\frac{2H}{f_0}\frac{df}{dt} = P_m - P_e = P_{diff} \tag{1}$$

Where :
- f_0 = Normal Frequency
- H = Inertia Moment constant
- df/dt = The rate of change of frequency
- P_m = Individual mechanic axis power of each machine for all the machines in the system.
- P_e = Individual electrical power of each machine for all the machines in the system.
- P_{diff} = The different between generated power and loaded power.

From equation above, the connection between frequency and power incompatibility can be obtained so that we can determine the amount of disturbance.

2) QV analysis

QV Analysis is one of the ways to investigate voltage instability problem in the system. Voltage at critical bus is plotted to reactive power at that bus. QV Analysis is the connection between reactive powers (Q) and accepts voltage (V_2) for value difference of active power (P). [1,7]

To determine the amount of load that will be released at every bus, voltage sensitivity at every bus has to be noticed. QV analysis is done by the following way [8]. The equation for active and reactive power is :

$$P_i = \sum_{j=1}^{n} V_i V_j Y_{ij} * \cos(\delta_{ij} - \theta_{ij}) \tag{2}$$

$$Q_i = \sum_{j=1}^{n} V_i V_j Y_{ij} * \sin(\delta_{ij} - \theta_{ij}) \tag{3}$$

So, for general equation, voltage sensitivity at every bus is :

$$\frac{dQ_i}{dV_i} = \sum_{j=1}^{n} V_i V_j Y_{ij} * \sin(\delta_{ij} - \theta_{ij}) \tag{4}$$

To predict this amount of load, there must be a reciprocal consideration from voltage sensitivity as a small part of the amount of reciprocity of voltage sensitivity. This reciprocity was considered because reciprocity will be smaller for higher slope so that the amount of load that will be released will be lower. Therefore, it can be said that,

$$\frac{dV}{dQ} = \left(1/\frac{dQ}{dV}\right) \tag{5}$$

$$\frac{dQ_i}{dV_i} = \left(1/\sum_{j=1}^{n} V_i V_j Y_{ij} * \sin\left(\delta_{ij} - \theta_{ij}\right)\right) \tag{6}$$

Equation above gives fractional values of voltage sensitivity at every bus. Direct connection between the amount of released load and dV/dQ value at every bus is $\frac{dV_i}{dQ_i}$ (the amount of released load from every bus). The addition of dV/dQ values from all the busses is :

$$\sum_{j=1}^{n} \frac{dV_i}{dQ_i} = \left(\frac{dV_1}{dQ_1} + \frac{dV_2}{dQ_2} + \ldots + \frac{dV_n}{dQ_n}\right) \tag{7}$$

Load that will be released at every bus is a small part of load total that need to be released for maintain system balance. dV/dQ fraction values at every bus is connected with total amount that is calculated and proportional to load total fraction that is released at every bus. The following is the representation :

$$\frac{\frac{dV_i}{dQ_i}}{\frac{dV_1}{dQ_1} + \frac{dV_2}{dQ_2} + \ldots + \frac{dV_n}{dQ_n}} \text{ (for every bus i)} \tag{8}$$

So, complex power equation (S) is :

$$S_i = \frac{\left(\frac{dV_i}{dQ_i}\right)}{\left(\sum_{j=1}^{n} \frac{dV_i}{dQ_i}\right)} P_{diff} \tag{9}$$

Where :
- dQ/dV = Voltage Sensitivity
- dV/dQ = Reciprocity of voltage sensitivity

Y = Admittance

S = Complex Power

III. Impact of Load Shedding Simulation at IEEE-9 Bus System With ETAP Power Station

In this simulation will be seen the impact of load shedding on frequency and voltage system, simulation will be performed at IEEE-9 Bus System with ETAP Power Station. The following are data at IEEE-9 Bus system that will be used to load shedding simulation using PV and QV analysis :

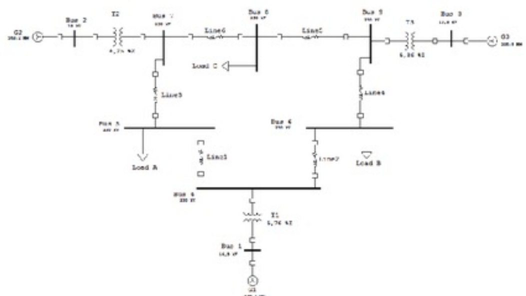

Fig. 1. Single Line Diagram Example of IEEE 9 Bus

Figure 1 show the picture of single line of IEEE – 9 Bus.

TABLE I. GENERATOR DATA

Variable	Generation		
	G1	*G2*	*G3*
Power (MW)	247,5	163,2	108,8
Voltage (KV)	16,5	18	13,8
Frequency (Hz)	50		
Inertia moment	6,632	2,312	1,632

Table I show data from generator which is power, voltage, frequency and inertia moment.

TABLE II. DATA

Line	R1	X1	Y1	θ
Line 1	5,29	37,47117	0,0002773	81,96
Line 2	8,993	40,55667	0,0002489	77,49
Line 3	16,928	70,97417	0,0004821	76,58
Line 4	20,631	74,94167	0,0005639	74,60
Line 5	6,2951	44,436	0,0003293	81,93
Line 6	4,4965	31,74	0,0002348	81,93

Table II show data from transmission line which is resistance, reactance, admittance, and theta angle.

TABLE III. LOAD DATA

Load	Power (MVA)
Load A	135,532
Load B	92,449
Load C	102,637

Table III show data from power of each load

Two scenario of disturbance simulation will be performed at IEEE-9 Bus System, which is :

1. Generator loss
2. Bus loss

Generator that will be released is generator 3 and bus that will be released is bus 9. After performing the disturbance, frequency and voltage at every bus will be noted. The following are frequency and voltage data at every bus after disturbance :

a. Disturbance of generator loss (G3-Off)

TABLE IV. FREQUENCY DATA AT EVERY BUS

Bus	Duration Fault				
	1 s	*3 s*	*5 s*	*7 s*	*10 s*
	F (Hz)	*F (Hz)*	*F (Hz)*	*F (Hz)*	*F (Hz)*
Bus 1	49,03	47,14	45,44	44,02	42,54
Bus 2	49,08	47,12	45,42	43,95	42,57
Bus 3	49,06	47,19	45,43	43,98	42,56
Bus 4	49,04	47,16	45,43	44	42,55
Bus 5	49,05	47,18	45,43	43,99	42,56
Bus 6	49,05	47,17	45,43	43,99	42,56
Bus 7	49,07	47,2	45,42	43,97	42,57
Bus 8	49,06	47,19	45,42	43,97	42,56
Bus 9	49,06	47,19	45,43	43,98	42,56

Table IV show frequency data from every bus during disturbance of generator loss for 10 second. From that table, we can see that all busses experience frequency decrease during 3 until 10 second disturbance.

TABLE V. VOLTAGE DATA EVERY BUS

Bus	Duration Fault				
	1 s	*3 s*	*5 s*	*7 s*	*10 s*
	V (%)	*V (%)*	*V (%)*	*V (%)*	*V (%)*
Bus 1	103,54	102,41	100,67	98,74	95,29
Bus 2	101,71	99,45	96,91	94,87	90,18
Bus 3	101,61	99,82	97,6	95,67	91,41
Bus 4	101,89	100,38	98,41	96,54	92,66
Bus 5	99,12	97,36	95,24	93,45	89,32
Bus 6	100,29	98,7	96,66	94,81	90,84
Bus 7	101,48	99,43	97,04	95,09	90,57
Bus 8	100,26	98,31	96,01	94,11	89,72
Bus 9	101,61	99,82	97,04	95,67	91,41

Table V show voltage data from every bus during disturbance of generator loss for 10 second. From that table, we can see that bus that experience critical condition is bus 3 during 3 second disturbance.

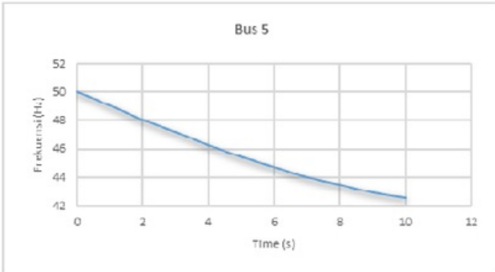

Fig. 2. Frequency Decrease at Bus 5

At figure 2, it is seen that frequency at bus 5 decrease during 10 second disturbance of generator loss in the system.

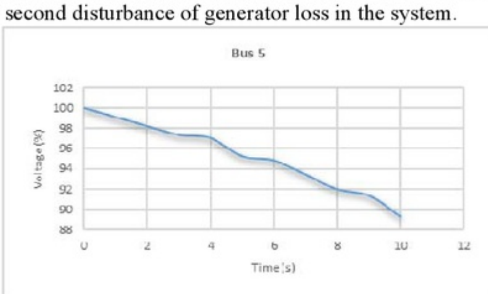

Fig. 3. Voltage Decrease at Bus 5

At figure 3, it is seen that voltage at bus 5 decrease during 10 second disturbance of generator loss in the system.

b. Disturbance of bus loss 9 (Bus 9-Off)

TABLE VI. FREQUENCY DATA EVERY BUS

Bus	Duration Fault				
	1 s	*3 s*	*5 s*	*7 s*	*10 s*
	F (Hz)	*F (Hz)*	*F (Hz)*	*F (Hz)*	*F (Hz)*
Bus 1	49,03	47,17	45,51	44,14	42,74
Bus 2	49,03	47,16	45,58	44,11	42,73
Bus 4	49,03	47,17	45,5	44,13	42,74
Bus 5	49,03	47,16	45,5	44,12	42,74
Bus 6	49,03	47,17	45,5	44,13	42,74
Bus 7	49,03	47,16	45,58	44,11	42,73
Bus 8	49,03	47,16	45,58	44,11	42,73

Table VI show frequency data at bus (1-2,4-8) during 10 second disturbance of bus lost. From that table, we can see that bus experience frequency decrease during 3 until 10 second disturbance.

TABLE VII. VOLTAGE DATA EVERY BUS

Bus	Duration Fault				
	1 s	*3 s*	*5 s*	*7 s*	*10 s*
	V (%)	*V (%)*	*V (%)*	*V (%)*	*V (%)*
Bus 1	103,63	102,57	100,9	98,82	100,9
Bus 2	101,07	99,27	96,79	93,84	96,79
Bus 4	101,98	100,77	98,91	96,69	98,91
Bus 5	98,77	97,4	95,36	92,82	95,36
Bus 6	100,82	99,62	97,78	95,5	97,78
Bus 7	100,7	99,04	96,68	93,84	96,68
Bus 8	99,12	97,48	95,16	92,37	95,16

Table VII show voltage data at bus (1-2,4-8) during 10 second disturbance of bus loss. From that table, we can see that bus that experience critical condition is bus 5 and bus 8 during disturbance.

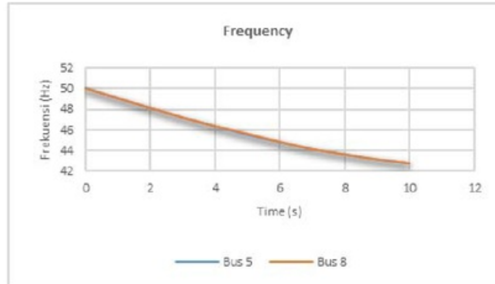

Fig. 4. Frequency Decrease at Bus 5 and 8

At figure 4, it can be seen that frequency at bus 5 and 8 decrease during 10 second disturbance of bus loss in the system.

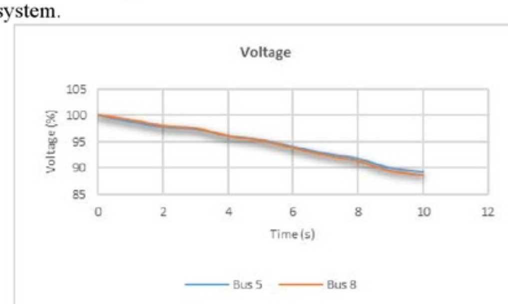

Fig. 5. Voltage Decrease at Bus 5 and 8

Figure 5 shows that frequency at bus 5 and 8 decrease during 10 second disturbance of bus loss in the system.

From the table of frequency and voltage data base at every bus for both disturbance, we can see that frequency and voltage decrease until below allowed value which is 47,5 Hz and 0,98 p.u. The release of load will be done at critical bus. Critical bus during disturbance of generator loss is bus 5, while critical bus during disturbance of bus loss is bus 5 and 8. Based on equation 1 and from those data, we can calculate the rate of change of frequency and inertia moment during disturbance, which are :

For the rate of change of frequency is $\frac{df}{dt} = \sum_{i=1}^{n} \frac{x_i - x_{i+1}}{n}$, with X_1 = 50 Hz, X_2 = 49,03 Hz, X_3 = 48,07 Hz, X_4 = 47,14 Hz,

$$\frac{df}{dt} = \frac{50 - 49,03 + 49,03 - 48,07 + 48,07 - 47,14}{3} = 0,95Hz,$$

that its for 1 bus critical, so for all bus critical is

$$\frac{df}{dt} = \sum_{i=1}^{n} \frac{x_i}{n}, \quad \frac{df}{dt} = \frac{0,95 + (0,93 \wedge 5) + (0,94 \wedge 3)}{9} = 0,93Hz$$

And for inertia moment is $H = \left(\sum_{i=1}^{n} H_i\right) aktif - (H) loss$,

$H = 4,472 - 1,632 = 2,84$.

Table VIII show the rate of change of frequency and inertia moment during disturbance.

TABLE VIII. THE RATE OF CHANGE OF FREQUENCY AND INERTIA MOMENT

Fault On System	The Rate Of Change Of Frequency	Inertia Moment
Generator Loss	0,93	2,84
Bus Loss	0,94	

1) The calculation of the different between generated power and loaded power (P_{diff})

Based on equation 1, the following are the calculation of the different between generated power and loaded power at every disturbance is :

$$\frac{2H}{f_0}\frac{df}{dt} = P_m - P_e = P_{diff}$$

$$P_{diff} = \frac{2*2,84}{50} 0,93 = 105,648MW$$

Table IX show the calculation of the different between generated power and loaded power (P_{diff}) for both disturbance.

TABLE IX. THE CALCULATION OF THE DIFFERENT BETWEEN GENERATED POWER AND LOADED POWER

Fault On System	P_{diff}
Generator Loss	105,648 MW
Bus Loss	106,784 MW

2) Released complex power calculation

Based on equation 9, complex power can be calculated by calculating voltage sensitivity value and fraction from voltage sensitivity of every critical bus. Voltage sensitivity value, voltage sensitivity fraction and the amount of voltage sensitivity for each disturbance are :

$$S_i = \frac{\left(\frac{dV_i}{dQ_i}\right)}{\left(\sum_{j=1}^{n}\frac{dV_i}{dQ_i}\right)} P_{diff}$$

For voltage sensitivity is $\frac{dQ_i}{dV_i} = \sum_{j=1}^{n} V_i V_j Y_{ij} * \sin(\delta_{ij} - \theta_{ij})$,

line 1 = $\frac{dQ}{dV} = 230 * 0,0002773 * \sin(0 - 81,96) = 63,141$

line 3 = $\frac{dQ}{dV} = 230 * 0,0004821 * \sin(0 - 76,58) = 107,556$

so line 1 + line 3 = 171,007. For voltage sensitivity fraction is $\frac{dV}{dQ} = \left(1/\frac{dQ}{dV}\right)$, $\frac{dV}{dQ} = (1/171,007) = 0,005847$. And for the amount of voltage sensitivity is $\sum_{j=1}^{n}\frac{dV_i}{dQ_i} = \left(\frac{dV_1}{dQ_1} + \frac{dV_2}{dQ_2} + ... + \frac{dV_n}{dQ_n}\right)$, so voltage sensitivity is $\sum_{j=1}^{n}\frac{dV}{dQ} = 0,005857$

Table X show the calculation of voltage sensitivity (dQ/dV), voltage sensitivity fraction (dV/dQ) and the amount of voltage sensitivity ($\sum_{i=1}^{n}\frac{dV_i}{dQ_i}$) from both disturbance.

TABLE X. THE CALCULATION OF VOLTAGE SENSITIVITY, VOLTAGE SENSITIVITY FRACTION AND THE AMOUNT OF VOLTAGE SENSITIVITY

Fault On System	Bus	$\frac{dQ}{dV}$	$\frac{dV}{dQ}$	$\sum_{i=1}^{n}\frac{dV_i}{dQ_i}$
Generator Loss	Bus 5	171,007	0,0058417	0,005847
Bus Loss	Bus 5	171,007	0,005847	0,019182
	Bus 6	74,988	0,013335	

We can calculate the amount of complex power that is released after knowing the quantity of required value to release load during disturbance. The amount of released load during each disturbance is :

$$S_i = \frac{(0,005847)}{(0,005847)} 105,648 = 105,648MVA$$

Table XI show the calculation of the amount of load power or complex power that will be released at each critical bus.

TABLE XI. THE AMOUNT OF RELEASED LOAD

Fault On System	Bus	Power (MVA)
Generator Loss	Bus 5	105,648
Bus Loss	Bus 5	32,54
	Bus 8	74,23

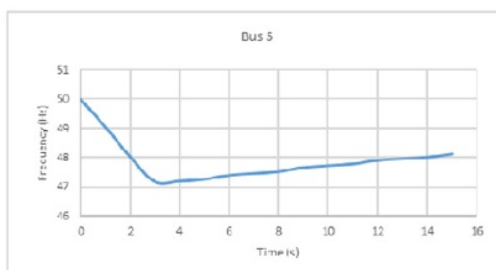

Fig. 6. Frequency Increase at bus 5

At figure 6, it is seen that frequency at bus 5 increase after load shedding of disturbance of loss generator. Frequency increase from 47,18 Hz at 3rd second to 48,12 Hz at 15th second.

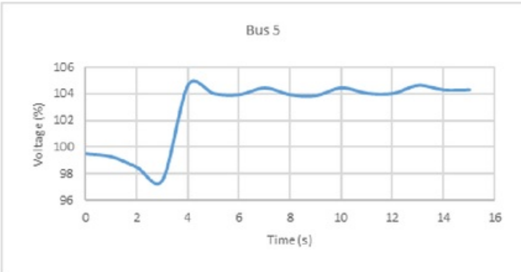

Fig. 7. Voltage Increase at Bus 5

At figure 7, it is seen that voltage at bus 5 increase after load shedding of disturbance of loss generator. Voltage increase from 97,51% at 3rd second to 104,26% at 15th second.

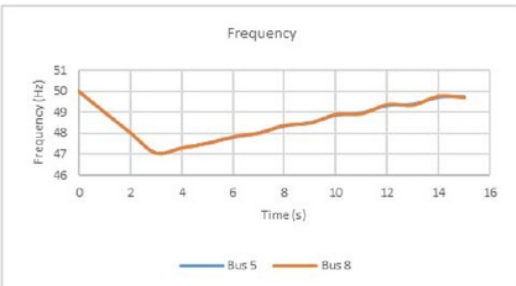

Fig. 8. Frequency Increase at Bus 5 and 8

At figure 8, it is seen that frequency at bus 5 and 8 increase after load shedding of disturbance of loss generator. Frequency increase from 47,04 Hz at 3rd second to 49,74 Hz at 15th second at bus 5, from 47,03 Hz at 3rd second to 49,68 at 15th second at bus 8.

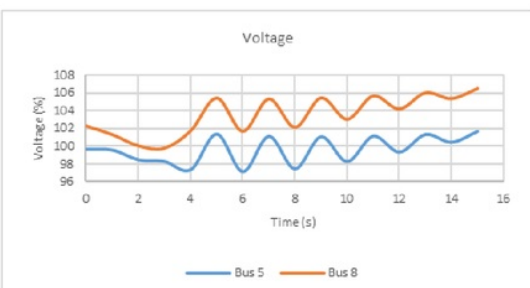

Fig. 9. Voltage Increase at Bus 5 and 8

At figure 9, it is seen that voltage at bus 5 and 8 increase after load shedding of disturbance of loss generator. Voltage increase from 98,3 % at 3rd second to 101,68 % at 15th second at bus 5, from 99,72% at 3rd second to 106,43 % at 15th second at bus 8.

IV. Conclusion

IEEE-9 Bus System with ETAP Power Station, frequency stability increase from 47,18 Hz to 48,12 Hz at bus 5 for the simulation of disturbance of loss generator, while for the simulation of disturbance of loss bus, frequency increase from 47,04 Hz to 49,74 Hz at bus 5 and from 47,03 Hz to 49,68 Hz at bus 8 and voltage stability increase from 97,51 % to 104,26 % at bus 5 for the simulation of disturbance of loss generator, while for the simulation of disturbance of bus loss, voltage increase from 98,3 % to 101,68 % at bus 5 and from 99,72 % to 106,43 % at bus 8. Frequency and voltage stability increase after load shedding using PV and QV analysis. There are disturbance of generator loss and bus loss in the system before load shedding that cause the decline of frequency and voltage stability.

Impact the load shedding on frequency and voltage system is increased. The load shedding calculation using PV and QV analysis. PV and QV analysis can be use at IEEE-9 Bus System with ETAP Power Station for load shedding simulation during disturbance and this analysis can also be used at another electrical power system.

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