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A Study on the Evaluation Algorithm for Performance Improvement in PV Modules

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Abstract – The location of PV systems in distribution system has been increased as one of countermeasure for global environmental issues. As the operation efficiency of PV systems is getting decreased year by year due to the aging phenomenon and maintenance problems, the optimal algorithm for state diagnosis in PV systems is required in order to improve operation performance in PV systems. The existing output prediction algorithms considering various parameters and conditions of PV modules could have complicated calculation process and then their results may have a possibility of significant prediction error. To solve these problems, this paper proposes an optimal prediction algorithm of PV system by using least square methods of linear regression analysis. And also, this paper presents a performance evaluation algorithm in PV modules based on the proposed optimal prediction algorithm of PV system. The simulation results show that the proposed algorithm is a practical tool of the state diagnosis for performance improvement in PV systems.

Keywords: PV system, Distribution system, Output prediction algorithm, Performance evaluation algorithm, Aging phenomenon, Least square method, Maintenance problem, State diagnosis

1. Introduction

The renewable energy sources such as wind power generation and photovoltaic (PV) system are being energetically interconnected with distribution system with the worldwide support of each government, as one of the solution to the energy and environment issues. And also, it has been actively promoted to expand the proportion of renewable energy up to 11% of total energy by 2030 under the green growth policy of Korea government. However, it is reported that the operation efficiency of PV system is getting decreased in a severe manner year by year with the aging phenomenon and maintenance problems. Therefore the optimal algorithm of output prediction and state diagnosis of PV system is getting required in order to improve operation performance of PV system. [1-4] But the conventional output prediction algorithms such as AMPP (Approximate maximum power point), FFv (Variable fill factor with constant series resistance) and Osterwald's, which should consider various parameters and several conditions of PV system, may have complicated computation procedure and then their results may have possibility of large prediction error. Further, existing state diagnosis systems are difficult to find abnormal state of PV modules like aging and damage because it has simple monitoring system by only measuring output data of inverter of PV system. [5, 6]

Under these backgrounds, this paper proposes an optimal prediction algorithm of PV system by using least square methods of linear regression analysis in order to reduce the prediction error and avoid complicated computation process. And also, this paper presents a performance evaluation algorithm using the proposed prediction algorithm of PV system and then implements the performance improvement system based on the monitoring system of each PV modules. From the simulation results, it is clear that the proposed algorithms are useful method of the state diagnosis for performance improvement in PV systems. [7-9]

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2. Degradation Characteristic of PV System

Existing state diagnosis systems are difficult to find abnormal state of PV modules such as aging and damage because it has simple monitoring system only measuring output data of inverter of PV system and monitoring PV module by web camera as shown in Fig. 1.

Although life span of PV modules may be more than 20

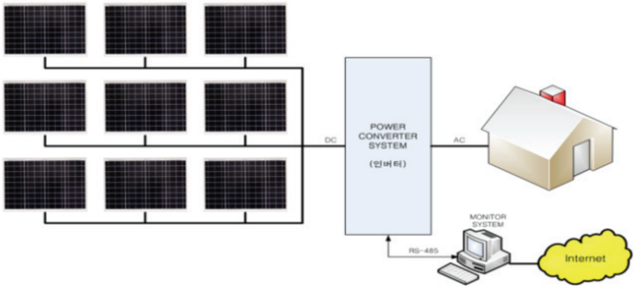


Fig. 1. Existing monitoring systems

Table 1. Cumulative power loss with aging (unit : %)

Annual	1	2	3	4	5	6	7	8	9	10	11	Cumulative loss
Remains	96.3	92.7	89.3	86.0	82.8	79.7	76.8	73.9	71.2	68.5	66.0	-
Loss	3.7	7.3	107	14.0	17.2	20.3	23.2	26.1	28.8	31.5	34.0	216.8

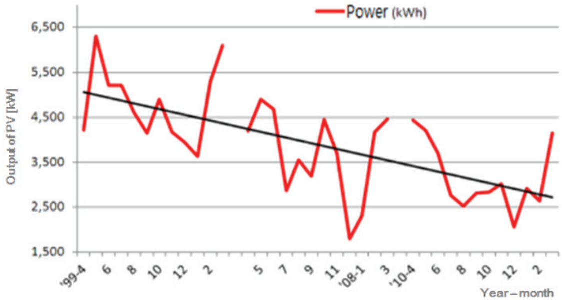


Fig. 2. Aging test result of KEPRI

years, the degradation of performance due to the aging phenomena in PV modules with the exposal to the outdoor environment has caused the huge power loss and decreased the total efficiency of PV system. The aging test results of 50kW class PV system are performed by Korea Electric Power Research Institute (KEPRI) as shown in Fig. 2 and Table 1. From the report, there is around 34% of cumulative power loss during 11 years after initial installation of the PV module. Namely, it is about 3.7% of cumulative power loss every year. [10, 11]

3. Performance Evaluation algorithm of PV System

3.1 Conventional prediction method of output power

Many kinds of conventional output prediction methods of PV module such as AMPP, FFv, and Osterwald's have been developed. AMPP algorithm among these method, considering short circuit current (I_{sc}) and open circuit voltage (V_{oc}) based on the standard test conditions (STC) and the solar radiation amount as shown in Eq. (1) and Eq. (2) has been widely used in the prediction method. And also, the maximum current (I_M) and the maximum voltage (V_M) of Eq. (5) and Eq. (6) can be calculated by relationship between short circuit current and open circuit voltage of Eq. (1) and Eq. (2) and the coefficient equation of Eq. (3) and Eq. (4). Finally, the output prediction of AMPP algorithm can be obtained as shown in Eq. (7).

$$I_{sc} = \frac{G_i}{G_i^*} \times I_{sc}^* \tag{1}$$

$$V_{oc} = V_{oc}^* - \beta \times (T_c - 25) \tag{2}$$

$$a = v_{oc} + 1 - 2 \times v_{oc} \times r_s \tag{3}$$

$$b = \frac{a}{1+a} \tag{4}$$

$$I_M = I_{sc} \times \left(1 - a^{-b}\right) \tag{5}$$

$$V_M = V_{oc} \times \left[1 - \frac{b}{v_{oc}} \times \ln a - r_s \times \left(1 - a^{-b}\right)\right] \tag{6}$$

$$P_{max} = V_M \times I_M \tag{7}$$

where, G_i is solar radiation measured, G_i^* is solar radiation at STC, I_{sc}^* is short circuit current at STC, V_{oc}^* is open circuit voltage at STC, β is voltage factor by temperature condition, T_c is back sheet temperature of PV module, v_{oc} is normalized open circuit voltage and r_s is series internal resistance.

3.2 New prediction algorithm of output power

As mentioned earlier, the conventional output prediction algorithms which should deal with various parameters of PV modules and weather conditions may have complicated process and then their prediction results may have possibility of large computation error. To overcome these problems, this paper proposes the idea of relationship between output characteristic of PV modules and weather conditions based on the measured data of real PV site. [12] Furthermore, this paper proposes optimal prediction algorithm of PV system by using least square methods of linear regression analysis in order to avoid complex computation procedure and reduce the prediction error.

3.2.1 Operation characteristics of PV system

The relationship between the output of PV modules and weather conditions such as temperature and solar radiation can be analyzed as shown in Fig. 3 and Fig. 4, which show the distribution characteristics measured at every 15 minutes during one month (April, 2013) in real PV site of Korea Conformity Laboratories system. It is clear that Fig. 3 shows very weak relationship between output of PV modules and temperature, but Fig. 4 shows strong relationship between output of PV modules and solar radiation. Therefore this paper will concentrate on the latter

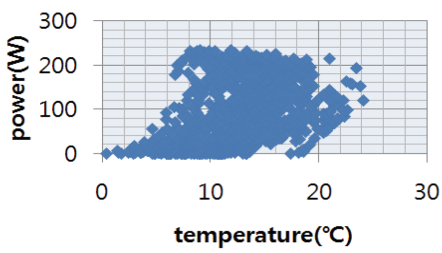


Fig. 3. Distribution characteristics of output and temperature

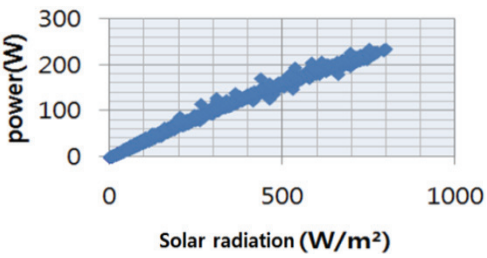


Fig. 4. Distribution characteristics of output and solar radiation

idea, relationship between output of PV module and solar radiation characteristics.

3.2.2 Novel prediction algorithm of output power

In order to improve the accuracy of output prediction at PV system, a concept of standard temperature conversion equation considering coefficient of temperature efficiency (γ) and the temperature measured at time interval of t(T_t) is introduced by Eq. (8),

$$P^*_{(t)} = P_{(t)} + \gamma\left(T_{(t)} - 25\right) \tag{8}$$

where, $P^*_{(t)}$ is output of PV module at standard temperature (25℃) and $P_{(t)}$ is measured output of PV module.

By combining the distribution characteristics of PV module in Fig. 3 and Fig. 4 and the standard temperature conversion equation of Eq. (8), output prediction equation using the quadratic linear regression method can be formulated by

$$P^*_{(t)} = \alpha X^2_{(t)} + \beta X_{(t)} + e_{(t)} \tag{9}$$

where, $X_{(t)}$ is solar radiation, α and β are linear coefficients and $e_{(t)}$ is error.

To solve the linear coefficients of α, β in Eq. (9), the least square method to minimize error is introduced by

$$S = \sum(P^*_{(t)} - \alpha X^2_{(t)} - \beta X_{(t)})^2 = \sum e^2_{(t)} \tag{10}$$

and then, obtaining the derivatives for α, β,

$$\frac{\partial S}{\partial \alpha} = \sum(\alpha X^4_{(t)} + \beta X^3_{(t)} - P^*_{(t)} X^2_{(t)}) = 0 \tag{11}$$

$$\frac{\partial S}{\partial \beta} = \sum(\alpha X^3_{(t)} + \beta X^2_{(t)} - P^*_{(t)} X_{(t)}) = 0 \tag{12}$$

Solving the equation for α and β in Eq. (9) cannot provide a linear equation. Therefore, the least square method is introduced in order to find out linear coefficients of α and β, it can be obtained as follows.

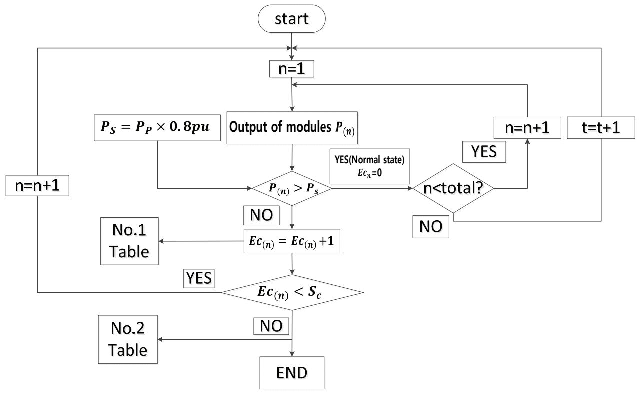


Fig. 5. Performance evaluation algorithm of PV modules

$$\alpha = \frac{\sum P^*_{(t)} X^2_{(t)} \sum X^2_{(t)} + \sum P^*_{(t)} X_{(t)} \sum X^3_{(t)}}{\left(\sum X^3_{(t)}\right)^2 - \sum X^4_{(t)} \sum X^2_{(t)}} \tag{13}$$

$$\beta = \frac{\sum X^4_{(t)} \left(\sum P^*_{(t)} X^2_{(t)} \sum X^2_{(t)} + \sum P^*_{(t)} X_{(t)} \sum X^3_{(t)}\right)}{\sum X^3_{(t)} (\left(\sum X^3_{(t)}\right)^2 - \sum X^4_{(t)} \sum X^2_{(t)}) - \frac{\sum P^*_{(t)} X^2_{(t)}}{\sum X^3_{(t)}}} \tag{14}$$

3.3 Performance evaluation algorithm of PV system

Based on the proposed output prediction algorithm of PV system as mentioned earlier, the performance evaluation procedure of PV modules can be expressed as shown in Fig. 5. Firstly, the output prediction value (P_p) of PV module is calculated by using the linear regression analysis method like Eq. (9). And then, the criteria value (P_s) of abnormal state for PV modules is defined as 0.8pu of the prediction value (P_p), which is derived from the experience value of abnormal PV modules. In next process, the measured output of n^{th} PV module ($P_{(n)}$) is compared with the criteria value (P_s) in order to evaluate the state of PV modules. If $P_{(n)}$ is bigger than P_s, n^{th} PV module is evaluated as normal state. However, if $P_{(n)}$ is smaller than Ps, n^{th} PV module is evaluated as temporarily abnormal state and also the iteration value ($Ec_{(n)}$) is getting increased. By repeating the process at each time interval, the PV modules are evaluated as abnormal state if the accumulated iteration values exceed the reference setting value (S_c), which is decided by the weather conditions like shading of cloud.

4. Implementation of Performance Evaluation System for PV System

4.1 Configuration of performance evaluation system

In order to evaluate state of module in PV system, the performance evaluation system for PV system is

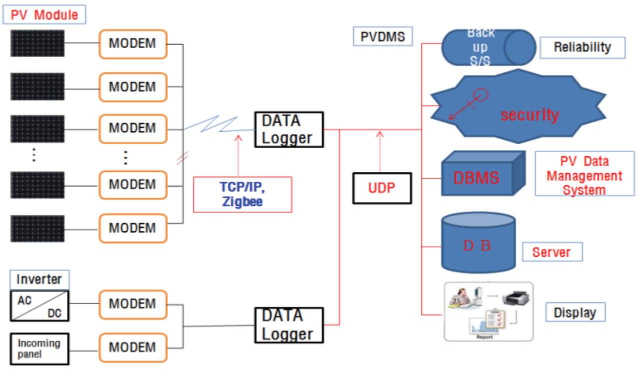


Fig. 6. Performance evaluation system of PV system

implemented by the proposed method as shown in Fig. 6. Firstly, the data which was measured from sensor at PV module including voltage, current, temperature and radiation is transmitted to data-logger using the communication device. And then, transmitted data are stored at specified table of database server which is divided by each date type like voltage, current, temperature and radiation. Based on the stored date at table of database, output prediction of PV system and performance evaluation of PV module is analyzed by performance evaluation system for PV system which adopts the proposed method. Additionally, state diagnosis evaluation system can offer various function such as alert, trend analysis, event and report writing.

4.2 Database design

In order to carry out performance evaluation of PV modules, the stored data in database through the data-logger are categorized into operation and maintenance data as demonstrated in Table 2. The former includes surrounding climate data, power conditioning system data and PV module data and the latter is malfunction information data, output prediction data and temporary storage data.

Based on the proposed algorithm mentioned earlier, this paper has implemented performance evaluation system for PV system using the Autobase software. And also, in order to provide various functions to operator, it is designed to carry out state diagnosis of PV modules by using data transferred in remote PV sites and to store evaluation results of state diagnosis at database. The normal monitoring and control menu of performance evaluation system is designed for operator to easily access the operation and maintenance information as shown in Fig. 7.

Table 2. Table item of database

	Table item	*Usage(Save and Analysis)*
Operation data	environment inverter modules	Collected environment information inverter information data modules data
Maintenance data	predict output	Predict values of PV modules temporary data of abnormal modules information of abnormal modules

Fig. 7. Monitoring function of state diagnosis system

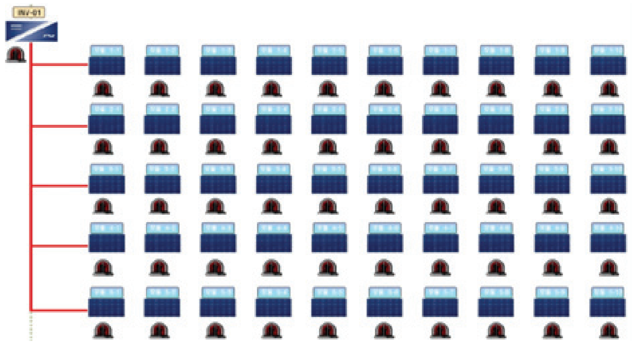


Fig. 8. Warning function for abnormal state

Furthermore, abnormal menu as shown in Fig. 8 is designed to promptly find out abnormal PV modules by adapting pop-up function like red warning light and warning window, at array configuration of PV system.

5. Case studies

5.1 Output prediction analysis

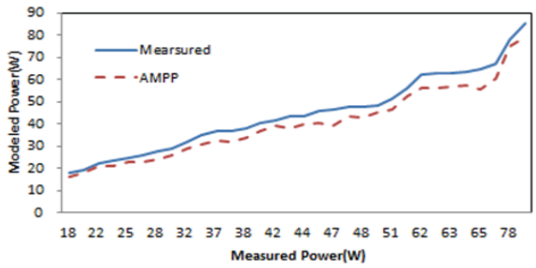
Table 3 shows the measurement data of 250W PV module installed in Korea Conformity Laboratories during one month on April, 2013. “Where, P_{MAX} is maximum power of PV module, V_{mp} is voltage of maximum power point, I_{mp} is current of maximum power point, FF is fill factor, Solar45 is vertical solar radiation and Solar00 is horizontal solar radiation”. By using Table 3, the comparison results between the proposed output prediction algorithm and the conventional output prediction algorithms are shown in Table 4 and Fig. 9. It is clear that the conventional output prediction algorithms such as FFv, Osterwald’s and AMPP considering various parameters of PV modules and weather conditions have big prediction error of 9.5% to 27.08%, however the proposed method (LRM: liner regression method) considering the relationship between the recent solar radiation and output of PV modules only has small prediction error of 2.3%. Where, error rate is obtained by comparing real measurement data with each

Table 3. Measured data of PV module

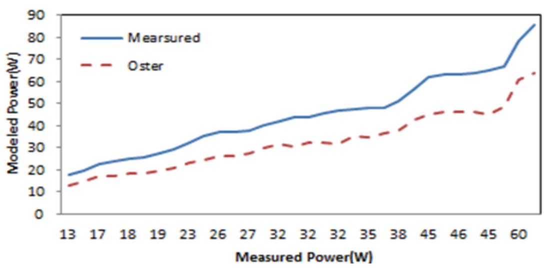
Date	Time	V_{OC} (V)	I_{SC} (A)	P_{MAX} (W)	V_{mp} (V)	I_{mp} (A)	FF(%)	Temp(℃)	Solar45(W/㎡)	Solar00(W/㎡)
2013-04-02	09:48:02	35.44	0.97	29.19	30.48	0.96	85.69	7.2	77	106
	10:48:02	35.83	1.46	41.89	30.63	1.37	79.95	8.4	118	141
	11:48:02	36.38	2.19	63.77	30.74	2.07	80.19	7.9	173	224
	12:48:02	35.99	1.22	36.81	30.59	1.20	83.60	6.5	97	123
	13:48:02	36.19	1.65	48.23	30.94	1.56	80.68	7.6	136	159
	14:48:02	36.11	1.55	46.81	30.87	1.51	83.64	8.8	119	179
	15:48:02	37.45	5.21	159.45	30.33	5.26	81.62	10.8	486	530
	16:48:02	35.13	0.80	22.43	29.86	0.75	79.44	8.5	63	79

Table 4. Comparison results of prediction algorithm

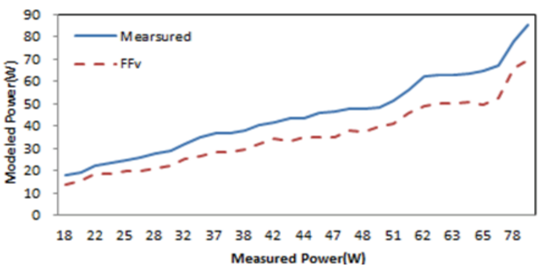
Date	Time(hh-mm-ss)	Power(W)	Temp(℃)	Insolation(W/㎡)	AMPP(W)	FFv(W)	Oster(W)	L.R.M(W)
2013-04-02	09:48:02	29.19	7.2	77	25.83	22.50	27.35	38.23
	10:48:02	41.89	8.4	118	39.13	34.48	31.60	44.14
	11:48:02	63.77	7.9	173	57.64	50.55	46.43	64.09
	12:48:02	36.82	6.5	97	32.76	28.34	26.18	36.37
	13:48:02	48.23	7.6	136	45.44	39.73	36.54	50.73
	14:48:02	46.81	8.8	119	39.31	34.77	31.82	44.51
	15:48:02	159.45	10.8	486	157.66	14204	128.92	166.06
	16:48	22.43	8.5	63	20.87	18.41	16.87	23.59
Error rate					9.50%	20.58%	27.08%	2.27%



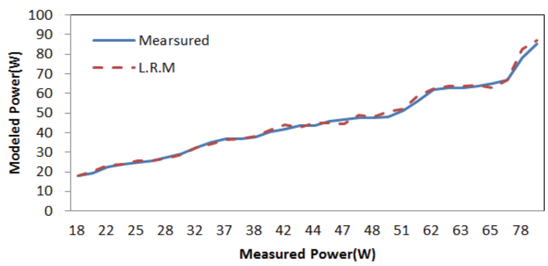
(a) AMPP



(c) Osterwald



(b) FFv



(d) Proposed method (liner regression method)

Fig. 9. Error characteristic of each prediction algorithm

calculated prediction data. Therefore, it is confirmed that the proposed method has an excellent performance for output prediction of PV system.

5.2. Performance evaluation algorithm analysis

By using the proposed method, this paper performed the simulation for the 12.5kW PV system located at Korea University of Technology and Education, which has a total of 50 modules and consists of 5 strings with 10 modules. It is assumed that Table 5 shows potential abnormal modules at each time interval, meaning that the measured output of PV module is less than criteria value as shown in Fig 5. Therefore, if a PV module is potential abnormal module in series three times, it is finally evaluated as an abnormal module. For example, [1-3] module can be evaluated as abnormal module because it is potential abnormal module from first time interval to third time interval consecutively, but [1-5] module is not abnormal module because it is potential abnormal module from first time interval to second time interval.

The state diagnosis system implemented by the proposed method as shown in Fig 10, can successfully find out the five abnormal PV modules of [1-3], [2-5], [3-8], [4-6] and

Table 5. Potential abnormal PV modules

Time interval	Potential Abnormal modules
1st	[1-3], [1-4], [2-5], [3-2], [3-9]. [4-6], [5-4]
2nd	[1-3], [1-5], [2-5], [3-2], [3-8]. [4-6], [5-4]
3rd	[1-3], [1-5], [2-5], [2-6], [3-8]. [4-6], [5-4]
4th	[1-1], [1-2], [2-5], [3-2], [3-8]. [5-0], [5-4]

*[a-b] : a is string number and b is module number

Fig. 10. Menu of performance evaluation system

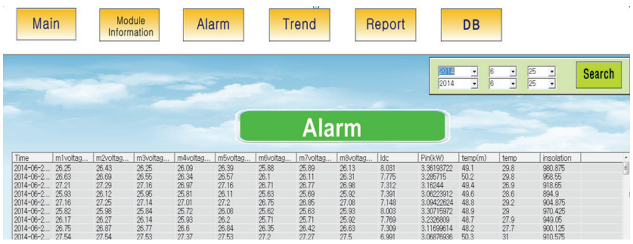


Fig. 11. Abnormal information in database

[5-4], which is bigger than counting number (3 iterations), and also show abnormal information to the operator with a pop-up alert menu. And also, the abnormal state module can be stored at the table in database server as shown in Fig. 11. Therefore, it is clear that the proposed method is a useful tool of the state diagnosis for performance improvement in PV systems.

6. Conclusions

This paper has proposed the optimal output prediction algorithm of PV system by using least square methods of linear regression analysis, and the performance evaluation algorithm of PV modules based on the proposed optimal prediction algorithm of PV system. The main results are summarized as follows.

(1) It is clear that the conventional output prediction algorithms such as FFv, Osterwald's and AMPP considering various parameters of PV modules and weather conditions have big prediction error of 9.5% to 27.08%, however the proposed method considering the relationship between the recent solar radiation and output of PV modules only has small prediction error of 2.3%. Therefore, it is confirmed that the proposed method has an excellent performance for output prediction of PV module.

(2) From the simulation result of the performance evaluation system, the proposed method can successfully find out the abnormal PV modules, and also show abnormal information to the operator with a pop-up alert menu. Therefore, it is clear that the proposed method is a useful tool of the state diagnosis for performance improvement in PV systems.

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