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Development of fast and accurate algorithm to extract the five parameters of photovoltaic modules

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ABSTRACT

The mathematical model of a photovoltaic (PV) cell helps in analyzing the PV system performance easily. In this paper, a new algorithm is developed to determine the values of five parameters model of photovoltaic module. The proposed method which is called extract the five parameters of photovoltaic modules (EFPPM) is used to find the optimum values of the I-V equation's parameters that fit with I-V curve. This method reduces the computation time of finding the values of PV model parameters. The proposed algorithm does not only reduce the computation time but it provides accurate values of PV model's parameters. A comparison with conventional algorithm shows superiority of the proposed EFPPM in term of computation speed. The results show that the reduction of the computation time reach nearly twenty-one times faster. The results also clarify that the I-V and P-V curves of EFPPM are exactly the same as provided by data sheets

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NOMENCLATURE

a	Ideality factor of the diode
G	Solar irradiation
G_n	Solar irradiation at STC condition
fI	Output current of PV cell
I_d	Shockley diode current
I_{mp}	Current of the cell at MPP
I_o	Reverse saturation current of the cell
$I_{o,n}$	Nominal reverse saturation current of the cell at STC condition
I_{pv}	Incident light current of the cell
$I_{pv,n}$	Nominal incident light current of the cell at STC condition
I_{sc}	Short circuit current of the cell
$I_{sc,n}$	Nominal short circuit current of the cell at STC condition
k	Boltzmann constant (k=1.3806503*10^{-23} J/K)
KCL	Kirchhoff's current law (KCL)
K_i	Temperature coefficient of I_{sc}
K_v	Temperature coefficient of V_{oc}

Np	Number of parallel cells
Ns	Number of series cells
$P_{max,e}$	Maximum power point provided by datasheet
$P_{max,m}$	Maximum power point provided by model
q	Electron charge (1.60217646*10^{-19} C)
R_s	Series resistance
$R_{s,pre}$	Previous value of R_s
R_p	Parallel resistance
$R_{p,pre}$	Previous value of R_p
$R_{p,min}$	Initial value of R_p
STC	Standard Test Condition
T	Absolute temperature of the cell in Kelvin
T_a	Ambient temperature.
T_n	Absolute temperature of the cell in Kelvin at STC condition
$\|\varepsilon\|$	Absolute error
V	Output voltage of PV
V_{mp}	Voltage at MPP
V_{oc}	Open circuit voltage
$V_{oc,n}$	Open circuit voltage
ΔP_{max}	Difference between $P_{max,e}$ and $P_{max,m}$
$\Delta P_{max,pre}$	The previous value of ΔP_{max}
V_t	Thermal voltage at 25 C^o

1. INTRODUCTION

A remarkable percentage of the used energy is produced by the fossil fuel. The CO_2 and many other harmful gases that produced as a result of the fuel's combustion cause many problems to the earth's environment such as Global Warming. Meanwhile, some studies prove that the fossil fuel has an end, therefore, the earth needs alternative energy resources. Sun is one of the most remarkable and renewable energy resources which can produce a useable clean energy. The Sun gives us (approximately) 170 PW [1]. Solar energy might not be the best solution nowadays because of the high cost but it might be for our future generation. Furthermore, a study shows that the renewable resources are growing fast and they become the second largest sources in 2015 and the first energy resources in 2035 [2]. Solar energy is the fastest growing source among them and it doubles each two years [3].

Solar cells convert the light from the sun into DC electrical energy and this occurs in some materials which have the ability to capture photons and release electrons and then current flows. Silicon is the main material in the industry to produce photovoltaic (PV) modules. In this paper, mathematical modelling is used in order to analyse the performance characteristics of the PV modules. Using the mathematical modelling makes the analysis much easier in contrast to the physical modelling [4]. By making mathematical modelling for the PV modules, manipulating and changing the parameters of a given module are easily achieved [5].

The output values (voltage, current and power) of PV models depend on irradiation, temperature and load current. The variations of these (irradiation, temperature and load current) play an important role in the modelling [6]. The single-diode model is not the only available model. In some papers, two and three-diode models are presented. The two-diode model in [7-11] is used for having higher accuracy. The second diode is added to involve the effect of the carrier recombination. The third diode is added in the three-diode model in [12] to involve the missing effects in the two-diode model. Single-diode model [13] is the most popular model because of the simplicity. It is categorized into two types which are four-parameter and five-parameter models. These five parameters including the parallel resistance are series resistance, incident light current, diode reverse saturation current, and ideality factor. The five-parameter model is considered more accurate and widely applied than the four-parameter model [14].

To extract these five parameters, several methods were applied. One method is to identify the parameters using the curve-fitting for the experimental data collected under specially controlled environment (SCE) such as sun simulator [8]. Deferent methods such as neural network (NN) and neuro-fuzzy model are used. NN model [15, 16] has a drawback which is the need of much data for training the neural network while neuro-fuzzy model needs fewer data [17].

Another method is to extract the parameters from driven equations with the help of the electrical specification data of the solar module provided in datasheets [18, 19], which are: the nominal short-circuit current ($I_{sc,n}$), nominal open-circuit voltage ($V_{oc,n}$), experimental peak output power ($P_{max,e}$), voltage at MPP (V_{mpp}), current at MPP (I_{mpp}), the temperature coefficient of the open-circuit voltage (K_v), the temperature coefficient of the short-circuit current (K_i) and the temperature at the nominal operating cell temperature (NOCT) under Standard Test Condition (STC). This method is much more reliable because the parameters of the model are computed mathematically using reliable data (datasheet). Therefore, it produces more accurate models, but in the price of time. It uses iteration methods, therefore, it consume too much time to find the model parameters. This paper tries to solve the unbearable time-consumption. In the meantime, it produces an accurate model. In this paper, we start with the methodology that includes model of a solar cell and the proposed modelling algorithm (section 2). Then, KC200GT solar array is used in section 3 to examine the EFPPM's accuracy and speed and compare with Villalva's modelling algorithm [24]. Lastly, section 4 displays the conclusion.

2. RESEARCH METHOD

2.1. Model of a solar cell

There are two popular types of cell models. The first model depends on one diode and it is called single-diode model [20, 21]. While the second type depends on two diodes and it is called double-diode model [8]. However, the double-diode model has better accurate results, but it has too many complicated equations. The single-diode model has also accurate results and easier mathematical expressions [22]. Therefore, Villalva's algorithm is based on single diode model as in Figure 1.

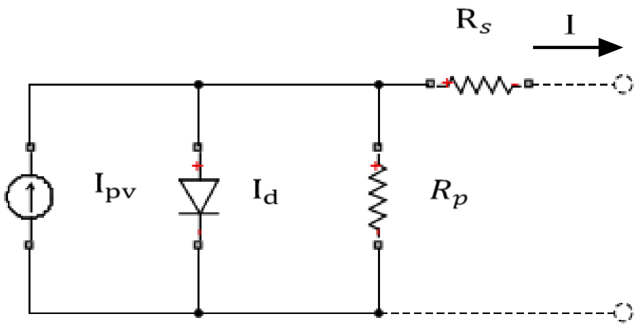


Figure 1. Practical solar cell model

Villalva's algorithm has many improvements for calculating the PV model parameters as will be clarified later. Therefore an accurate and reliable PV model can be obtained. This method depends mainly on finding the model parameters using three point in the I-V curve. The three points which are open circuit, short circuit and maximum power point are easily obtained by the data provided in datasheets under STCs. The I-V equation for a PV array is:

$$I = I_{pv} - I_o \left[exp\left(\frac{q(V+IR_s)}{akT}\right) - 1\right] - \frac{V+IR_s}{R_p} \tag{1}$$

where I_{pv} and I_o are the photocurrent and the diode reverse saturation current, respectively, q is the electron charge ($1.6 \times 10^{-19}\ C$), k is the Boltzmann constant (1.38×10^{-23} J/K), a is the modified ideal factor, R_s and R_p are, respectively, the series and parallel resistance (Ω), and T is the cell temperature (K). The (1) is obtained from Figure 1 based on Kirchhoff's current law (KCL), where the diode current I_d is substituted by;

$$I_d = I_o \left[exp\left(\frac{q(V+IR_s)}{akT}\right) - 1\right] \tag{2}$$

Adjusting (1) at the three points can lead to find the unknown parameters I_{pv}, I_o, R_p, R_s, and a. I_{pv} can be found by (3).

$$I_{pv} = [I_{pv,n} - K_i(T - T_n)]\frac{G}{G_N} \tag{3}$$

It is generally assumed I_{pv}=I_{sc} (Short circuit current of the cell) because the R_s is low and R_p is high. The diode saturation current is normally expressed as [23].

$$I_o = I_{o,n}\left(\frac{T_n}{T}\right)^3 \exp\left[\frac{qE_g}{aK}\left(\frac{1}{T_n}-\frac{1}{T}\right)\right] \tag{4}$$

The (4) can be replaced by (5) and provides an improvement for the PV model because the dependency on temperature is included using the voltage and current temperature coefficient (K_v and K_i) [24].

$$I_o = \frac{I_{sc,n}+K_i\Delta T}{exp\left[{(V_{oc,n}+K_v\Delta T)}/{aV_t}\right]-1} \tag{5}$$

Finding R_p and R_s is done based on that there is a point where the model maximum power point $P_{max,m}$ equals the datasheet maximum power point $P_{max,e}$ as in (6) [24]. Adjusting the I-V equation by incrementing R_s starts from zero and then finds R_p by (7). Incrementing R_s should be linearly with a small and fixed step increase in order to get the desired values of R_s and R_p.

$$P_{max,m} = V_{mp}\left\{I_{pv} - I_o\left[exp\left[\frac{(V_{mp}+I_{mp}R_s)}{aN_s}\frac{q}{kT}\right]-1\right] - \frac{V_{mp}+I_{mp}R_s}{R_p}\right\} = P_{max,e} \tag{6}$$

$$R_p = \frac{(V_{mp}+I_{mp}R_s)}{I_{pv}-I_o exp\left[\frac{(V_{mp}+I_{mp}R_s)}{aN_s}\frac{q}{kT}\right]+I_o-\frac{P_{max,e}}{V_{mp}}} \tag{7}$$

Further improve is developed by [24] using (8) which warrants more accurate matching between model I-V curve and real PV array I-V curve so $I_{pv} \neq I_{sc}$.

$$I_{pv,n} = \frac{R_p+R_s}{R_p}I_{sc,n} \tag{8}$$

The initial value of R_s is 0 while the intial value of R_p is obtained by:

$$R_{p,min} = \frac{V_{mp}}{I_{sc,n}-I_{mp}} - \frac{V_{oc,n}-V_{mp}}{I_{mp}} \tag{9}$$

2.2. Proposed algorithm

EFPPM is designed similar to Villalva's algorithm. However, in the designed EFPPM, dynamic incrementation is proposed instead of the static incrementation proposed in Villalva's algorithm. The dynamic incrementation is used to improve the speed of algorithm and reduces the computation time when finding the model parameters. The initial incrementation step in EFPPM is set to 0.1 (0.1 is considered a big step value because the value of R_s is small). Incrementing continues until the value of R_s jumps over the desired value. Then the last value of R_s before exceeding the desired value will be increased using a new increment step (the new increment step=the previous increment step divided by 10). These processes continue until matching the $P_{max,m}$ with $P_{max,e}$. The ideas are to use a dynamic increment step for R_s incrementation starting from a big value 0.1 until the best value of R_s and R_p are found. The static increment step is replaced by the dynamic increment step to reduce the iteration numbers of the modelling algorithm in [24]. Figure 2 shows the flowchart of the proposed EFPPM.

3. RESULTS AND DISCUSSION

EFPPM reduces the number of the iteration and has the same accuracy of the Villalva's algorithm. Reduction is done based on using dynamic incrementation. Table 1 shows the electrical characteristics of KC200GT solar array [25] provided by the datasheet. The KC200GT solar array is used here to create a PV model using EFPPM and the Villalva's algorithm and then makes a comparison between them.

Figures 3 and 4 show the I-V and P-V curves plotted for different values of R_s and R_p using both the Villalva's algorithm and EFPPM, respectively. As we notice, the plotted curves in Figures 3. (a) and (b) move toward left as R_s is slowly increased. In Villalva's algorithm, R_s starts from zero. The desired R_s *and* R_p are found when $P_{max,m}$ matches with $P_{max,e}$ using equation (6) as shown in Figure 3. (b). In Figures 4. (a) and (b), the plotted curves swing around MPP until the $P_{max,m}$ matches with $P_{max,e}$. Table 2 shows how R_s is changed in EFPPM. The desired R_s and R_p are 0.221 Ω and 415.76 Ω, respectively. Both methods the Villalva's algorithm and EFPPM produce same result of the desired R_s and R_p as shown in Figures 5. (a) and (b) but with different significant speed. They show that the model curves I-V and P-V exactly match with the experimental curves I-V and P-V of KC200GT solar array given by the datasheet at three points: short circuit point, MPP and open circuit point.

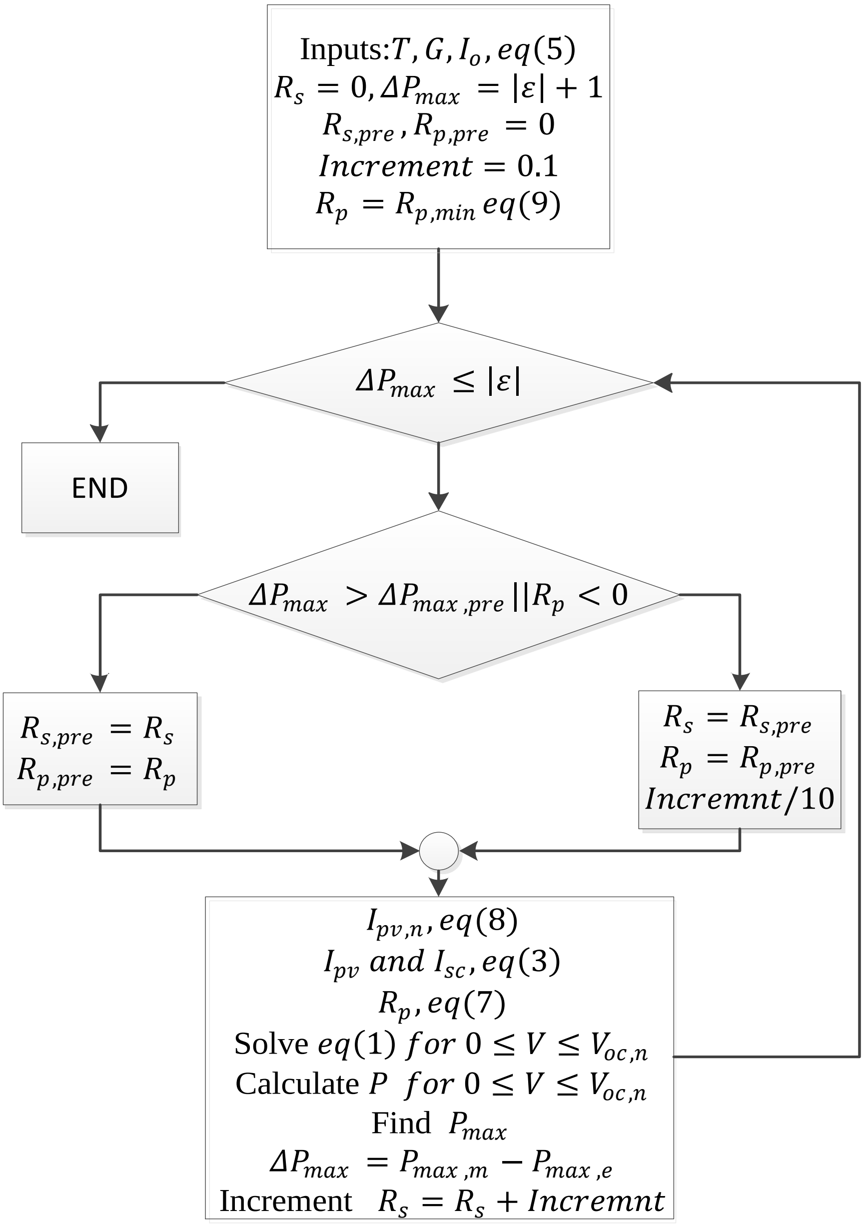
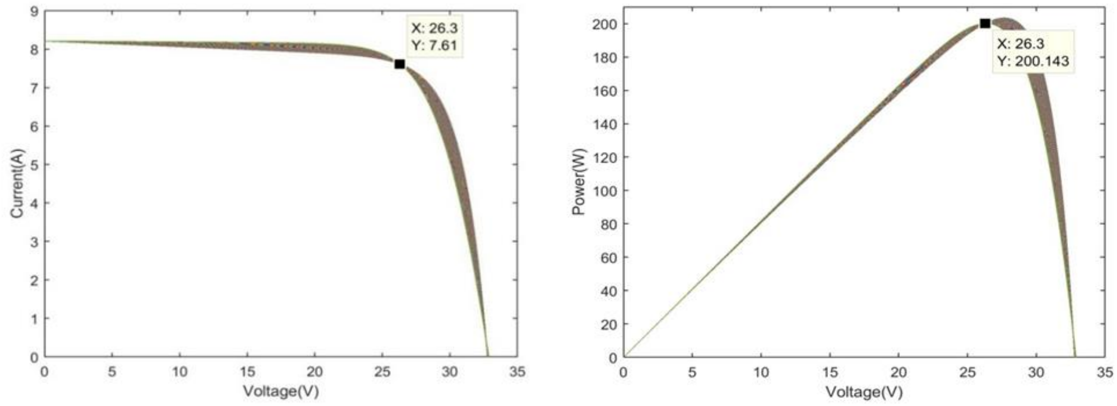


Figure 2. Flowchart of EFPPM

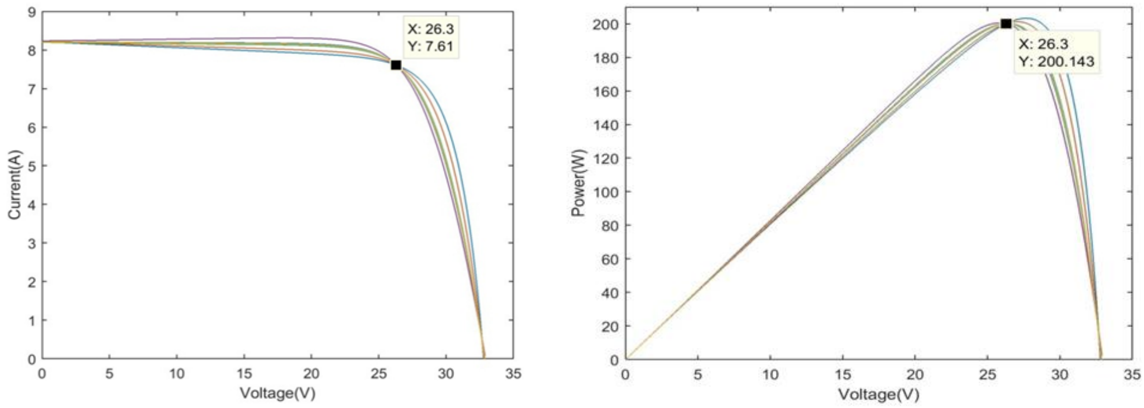
Table 1. Typical electrical characteristics of KC200GT module under STCs

parameter	value
$P_{max,e}$	200.143 W
V_{mp}	26.3 V
I_{mp}	7.61 A
$I_{sc,n}$	8.21 A
$V_{oc,n}$	32.9 V
K_i	0.0032 A/K
K_v	-0.1230 V/K
Ns	54



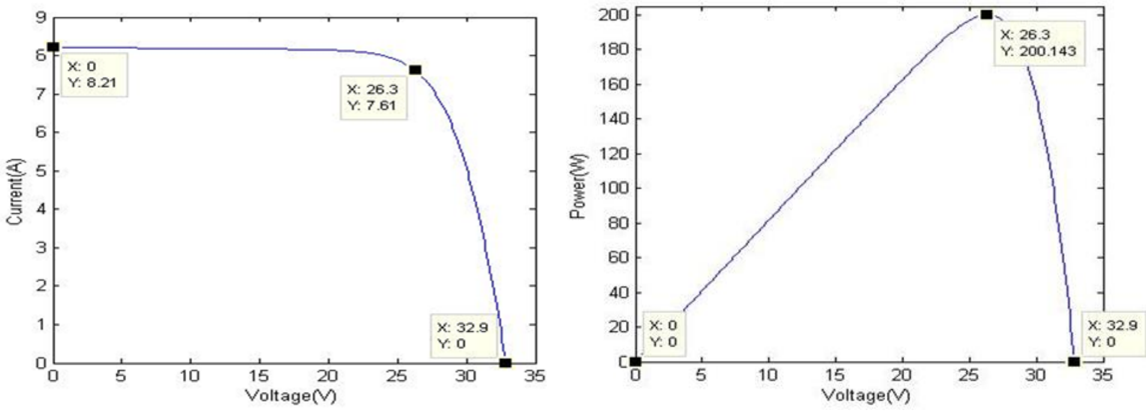
(a) (b)

Figure 3. (a) I-V and (b) P-V curves plotted for many values of R_s and R_p for the Villalva's algorithm



(a) (b)

Figure 4. (a) I-V and (b) P-V curves plotted for many values of R_s and R_p for EFPPM



(a) (b)

Figure 5. (a) I-V and (b) P-V curves plotted for the optimum value of R_s and R_p for both EFPPM and the Villalva's algorithm.

The number of plotted I-V and P-V curves until finding the optimum values of R_s and R_p using EFPPM is 10 while using the Villalva's algorithm is 221. In terms of computation time, EFPPM requires 5.7 Sec. when executed in the processor (2.0 GHz Intel Core 2 Duo T5800 compared to 123.4 sec. for Villalva's algorithm. This much time comes due to solving the nonlinear equation (1) for I ϵ $[0, I_{sc,n}]$ and V ϵ $[0, V_{oc,n}]$.

$I_{sc,n}$ and $V_{oc,n}$ are 8.21 and 32.9, respectively. The values of R_s used in the iteration process using EFPPM are listed in Table 2.

Table 2. R_s Incrementation values of EFPPM

R_s Values		
First Sequence	Second Sequence	Third Sequence
0	0.20	0.220
0.1	0.21	0.221
0.2	0.22	

The desired parameters values with a comparison between EFPPM and the Villalva's algorithm in term of iteration no and computation time are listed in Table 3. The table shows that both methods give same result but different computation time. Table 3 shows the superiority for EFPPM against Villalva's algorithm in term of time efficiency. Lastly, despite of the high accuracy of Villalva's algorithm, it consumes too much time to find the five parameters of the PV modules. Therefore, we need a modelling algorithm that produces high accurate PV models with acceptable computation time and that is available in EFPPM. EFPPM can be more effective with large solar arrays that have large R_s, because the reduction of time computation done by EFPPM will be more noticeable.

Table 3. Parameters of the adjusted model of the Kc200gt solar array at nominal operating conditions

Parameters	Villalva's algorithm [24]	EFPPM
$P_{max,e}$	200.143 W	200.143 W
V_{mp}	26.3 V	26.3 V
I_{mp}	7.61 A	7.61 A
$I_{sc,n}$	8.21 A	8.21 A
$V_{oc,n}$	32.9 V	32.9 V
a	1.3	1.3
I_{pv}	8.214 A	8.214 A
$I_{o,n}$	9.8225e-08	9.8225e-08
R_s	0.221	0.221
R_p	415.78	415.78
Iteration Num	221	**10**
Computation Time	123.447 Seconds	**5.725 Seconds**

4. CONCLUSION

Solar energy has some drawbacks such as high cost, recombination, shading, and day sunlight. Many researchers try to maximize the efficiency of photovoltaic system by studying the I-V and P-V characteristics curves. Mathematical modelling gives us an easy and accurate tool to analyse I-V and P-V characteristics curves. In this paper, the main objective is to overcome the slowness of the existing modelling algorithms. The proposed modelling algorithm (EFPPM) is a method to find the five unknown PV model parameters (a, I_o, I_{pv}, $R_s, and\ R_p$). Finding the PV model parameters is done based on adjusting the I-V curve in three points that are provided by datasheet (short circuit, open circuit, and MPP). An iterative process of increasing R_s and then find R_p and I_{pv} is the main key to adjust the I-V curve. This iteration processes, based on fixed increment, consumes much time because of solving nonlinear equation. An improvement is fulfilled by minimizing the number of the iterations. Instead of using fixed increment to find the optimum values of PV model parameters, a dynamic increment is used. The time consumed to find the model parameters of KC200GT solar array is 5.725 seconds using EFPPM instead of 123.447 seconds using a similar work. This result shows that EFPPM has superiority in term of the computation time.

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