Journal of Physics:
Conference Series

PAPER • OPEN ACCESS

Design of 30 kW three-phase string inverter using simulink

Design of 30 kW three-phase string inverter using simulink

Fauzi F[1], Yasin N[2], Leong J H[1] and Ismail B[3]

[1]School of Electrical Systems Engineering, Universiti Malaysia Perlis (UniMAP), Pauh Putra Campus, Arau, 02600, Perlis, Malaysia.
[2]UniCity Management Sdn. Bhd, No 24, Lower Ground Floor, Persiaran Putra, Taman Putra Utama, 01000, Kanagar Perlis.
[3]Centre of Excellence for Renewable Energy (CERE), School of Electrical Systems Engineering, Universiti Malaysia Perlis (UniMAP), Pauh Putra Campus, Arau, 02600, Perlis, Malaysia.

Email: fijay@unimap.edu.my

Abstract: This paper presents the design and simulation of a 30 kW DC to AC inverter. The inverter is designed based on the Zeverlution Pro 33K three-phase DC to AC inverter. Currently, there are 6 units of the inverters installed at 180 kW solar power plant located at Mukim Utan Aji, Perlis. So, in this paper, the results from the computer simulation will be compared to the site measurement conducted from this power plant. In this design, pulse with modulation (PWM) is used as the switching technique. Even though PWM offers the ease of LC filter design and low Total Harmonic Distortion (THD), the voltage amplitude of the sine wave output fails to achieve the required national grid parameters, i.e. 240 Vrms. To overcome this problem, a three-phase transformer has to be incorporated in the design to obtain the desired outputs. Results from computer simulation using SIMULINK show that the targeted AC parameters for all phases were achieved after comparing with the site measurement.

1. Introduction

Solar Power Plant at Mukim Utan Aji, Perlis, Malaysia
Perlis is the smallest state and located at northern Malaysia bordered with Thailand. The capital of the state, Kangar is located 400 km from Kuala Lumpur. Even though it is a small state, Perlis is blessed with sunshine throughout a year. The average temperature every month is always higher than 28^{o}C[1].This climate provides an opportunity to whoever wants to invest in solar energy and reap the benefit in the long term.

A solar power plant with maximum output of 180 kW was built by a private company back in 2016. The image of the solar power plant, taken from Google Earth is shown in Figure 1(a). From this figure, one can see that, at the site, 2 structures were built to mount solar panels on top of them. This type of structure is called building integrated photovoltaic (BIPV). Solar panels used for these building were supplied by Jinko Solar model JKM250P. Details of the important parameters are provided in Table 1.Figure 1(b) shows the picture of the power plant from close range.

Journal of Physics: Conference Series **1432** (2020) 012029 doi:10.1088/1742-6596/1432/1/012029

(a) (b)

Figure 1. (a) Picture of the power plant taken from Google Earth. (b) The 180 kW power plant viewed from close range

Table 1. The important parameters of JKM250P solar panel [2]

Model of the solar panel	Jinko Solar JKM250P
Maximum power per panel (W)	250 W
Maximum power voltage (V_{mp})	30.4 V
Maximum power current (I_{mp})	8.23 A
Open circuit voltage (V_{oc})	37.6 V
Short circuit current (I_{sc})	8.81 A

Overall, there are 720 pieces of solar panels and 6 inverters installed at the site. So, every inverter has to accommodate 120 panels. This means, the input for every inverter is equal to 30 kW, where the connection of 120 solar panels finally produces 49.4 A and 608 V of direct current and voltage respectively.

The inverters were supplied by ZeversolarGmBH and is shown Figure 2. The model of the inverter is Zeverlution Pro 33K. The power of the inverter is rated at 33 kW.

Figure 2. Zeverlution Pro 33K DC to AC inverter

Basic three-phase inverter

Basic three-phase inverter consist of 6 transistors as shown in Figure 3. The load can be connected in either star or delta. Detail explanations of three-phase inverterscan be found in this reference [3].

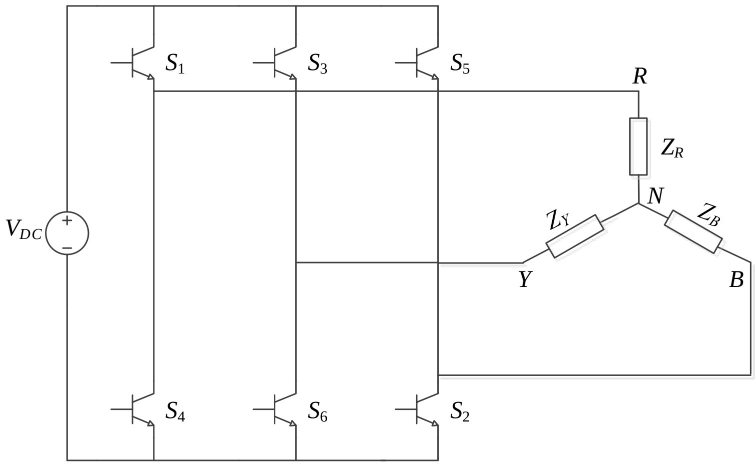


Figure 3. Basic three-phase inverter with star connected loads

Figure 4 shows the output voltages for every phase with respect to the neutral point, N as shown in Figure 3. It is important to note that the output voltages shown here have not been filtered yet. It means, the amplitude of the pure sine waves are not necessarily equal to $\frac{2}{3}V_{DC}$. To predict the amplitude of the fundamental frequency, Fourier Series has to be applied.

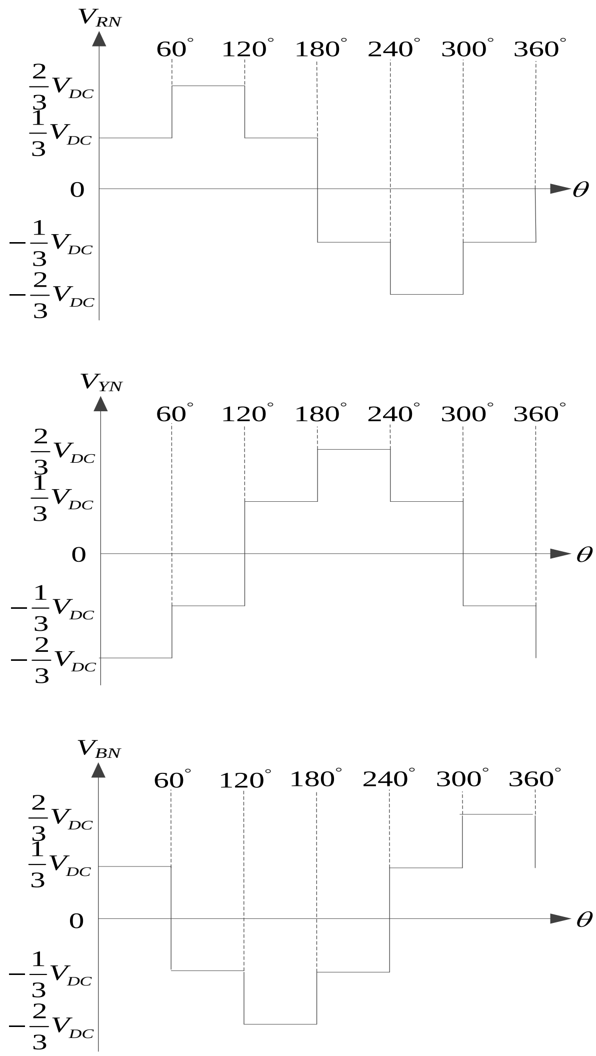


Figure 4. The output of three-phase inverter showing before filtering

Fourier series is necessary to determine the fundamental harmonic amplitude of the 'stepped' sinusoidal voltage. By only using waveform of V_{RN}in Figure 4, and assuming the period T = 20 ms, the $b_n$coefficient can be determined, where [4];

$$b_n = \frac{4}{0.02}\int_0^{0.00333}\frac{1}{3}V_{dc}\sin n\omega_o t dt + \frac{4}{0.02}\int_{0.00333}^{0.00667}\frac{2}{3}V_{dc}\sin n\omega_o t dt + \frac{4}{0.02}\int_{0.00667}^{0.010}\frac{1}{3}V_{dc}\sin n\omega_o t dt$$

For ease of analysis, the equation above is divided into three parts, where;

$$b_n = A + B + C$$

From *A*,

$$\begin{aligned} A &= \frac{4}{0.02}\int_0^{0.00333}\frac{1}{3}V_{dc}\sin n\omega_o t dt \\ &= \frac{200V_{dc}}{3}\left[\sin n314.2t\right]_0^{0.00333} \\ &= -\frac{200V_{dc}}{942.6n}\left[\cos n314.2(3.33\text{m}) - 1\right] \end{aligned}$$

If n = 1 and V_{dc} = 608 V, A = 64.65

From *B*,

$$\begin{aligned} B &= \frac{4}{0.02}\int_{0.00333}^{0.00667}\frac{2}{3}V_{dc}\sin n\omega_o t dt \\ &= \frac{400V_{dc}}{3}\left[\sin n314.2t\right]_{0.00333}^{0.00667} \\ &= -\frac{400V_{dc}}{942.6n}\left[\cos n314.2(6.67\text{m}) - \cos n314.2(3.33\text{m})\right] \end{aligned}$$

If n = 1 and V_{dc} = 608 V, B = 257.8
From C,

$$\begin{aligned} C &= \frac{4}{0.02}\int_{0.00333}^{0.00667}\frac{11}{3}V_{dc}\sin n\omega_o t dt \\ &= \frac{200V_{dc}}{3}\left[\sin n314.2t\right]_{0.00667}^{0.01} \\ &= -\frac{200V_{dc}}{942.6n}\left[\cos n314.2(10\text{m}) - \cos n314.2(6.67\text{m})\right] \end{aligned}$$

If n = 1 and V_{dc} = 608 V, C = 63.82

Finally, b_n = 386 V. By applying Fourier series, it is obvious that the fundamental harmonic amplitude of the 'stepped' sinusoidal voltage is not necessarily equal to $\frac{2}{3}V_{DC}$. By applying Fourier Series, the amplitude of the phase voltages of the inverter can be predicted to be 386 V (or 273 V_{rms}).

The 'stepped' sinusoidal AC voltages shown in Figure 4 is not favourable in the reality. It is because the 'stepped' sinusoidal voltage contains odd harmonics. (n = 3,5,7 etc.). These harmonics are difficult to filter using LC filter because they are located close to the fundamental harmonic[5].

Inverter design with Pulse Width Modulation (PWM).
In DC to AC converter design, pulse width modulation (PWM) is a well-known technique in reducing filter requirements[6]. Due the frequency modulation ratio (m_f), the next harmonics after the fundamental can be easily determined. This leads to smaller *LC* filter requirement if the harmonics are place far away for the fundamental frequency[7].

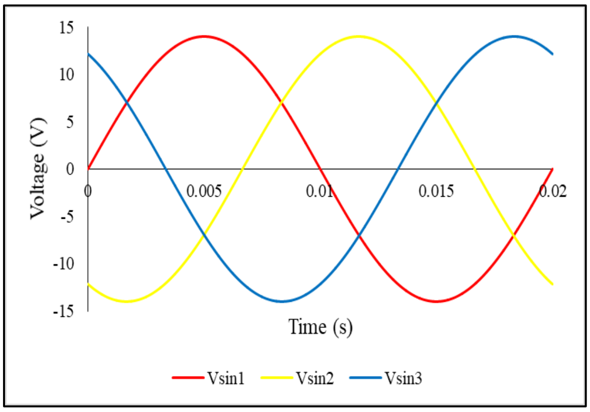
In addition, PWM also offer ease of controlling the amplitude of the sine wave output. By setting the amplitude modulation ratio, m_a, the amplitude of the fundamental harmonic, V_1 for the three-phase inverter is defined as [8];

$$V_1 = \frac{m_a V_{DC}}{2} \tag{1}$$

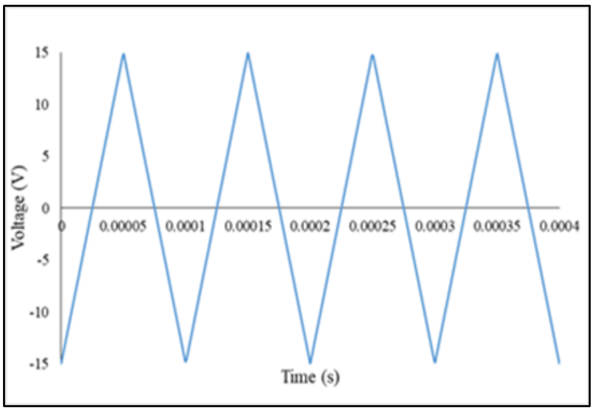
However, equation (1) clearly shows that three-phase inverter produces low fundamental amplitude at the output side. Even with $m_a = 1$, V_1 will equal half of the V_{DC}. That is why a three-phase transformershould also be incorporated in the inverter design to obtain the desired outputs.

2. Methodology

Simulation starts with the switching circuit for the 6 transistors. In this simulation, SIMULINK software is used. The three-phase reference voltages are shown in Figure 5(a). All of the AC voltages have frequency of 50 Hz and 14 Vamplitude.



(a)



(b)

Figure 5.(a) Three-phase reference voltages (b) Reference signal

The carrier signal (shown in Figure 5(b)) used for the comparison with the sinusoidal signals is a triangular wave. The frequency of the carrier signal is 10 kHz and amplitude of 15 V. This means the frequency modulation ratio, m_f equals to [9];

$$m_f = \frac{f_{carrier}}{f_{reference}} = 2000 \quad (2)$$

Meanwhile, the amplitude modulation ratio, m_a equals to [9];

$$m_a = \frac{V_{m,reference}}{V_{m,triangular}} = 0.933 \quad (3)$$

By utilising equation (1) the amplitude of the fundamental frequency at the inverter output equals to 283.6 V and the V_{rms}= 201 V. The inverter circuit constructed using SIMULINK is shown in Figure 6. Table 2 states all values of the electrical components as shown in Figure 6.

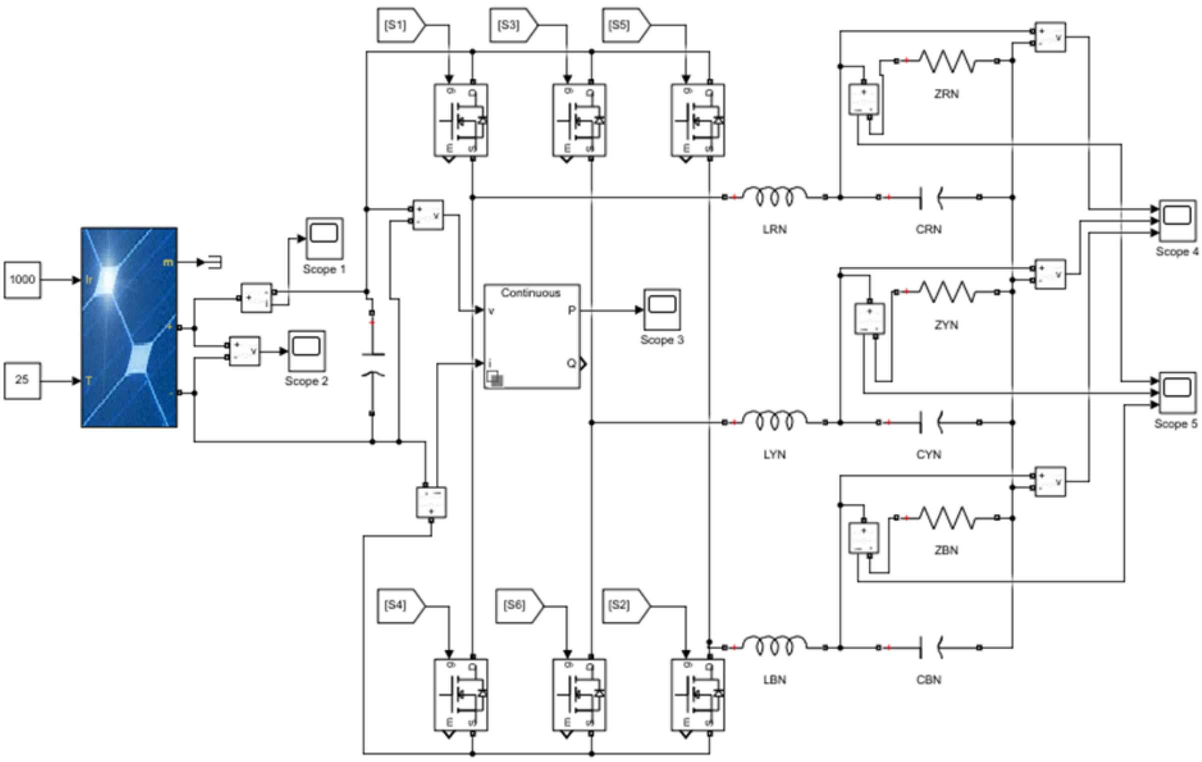


Figure 6. Three-phase inverter circuit built using SIMULINK

Table 2. Values of electrical components for Figure 7

Components	Remarks
Inductors	All inductors are 200 µH
Capacitors	All capacitors are 300 µF except the DC link = 400 µF
Resistors	All resistors are 4.05 Ω
MOSFETs	All MOSFETs have FET resistance = 0.1 Ω and internal diode resistance = 0.01 Ω
Scope 1	To measure DC input current (A)
Scope 2	To measure DC input voltage (V)
Scope 3	To measure true power (W)
Scope 4	To measure 3-phase output voltage (V_{rms}) (V)
Scope 5	To measure 3-phase output voltage (I_{rms}) (A)

Figure 7 shows the results from site measurement of the 180kW power plant. The voltage and current was recorded using Fluke 1750 power meter. It is worth noting that during the site measurement activity, one of the inverter was taken out for service. Thus only 5 inverters were working properly.

The result shows that the Zeverlution Pro 33K inverter is capable of producing smooth sinusoidal output voltages with 50 Hz frequency. The measurement shown, represents 3 phase voltage from red, yellow and blue phases. All of the voltages and currents were measured in rms values. From this figure, one can see that all currents are in same phase with their respective phase voltage. Meaning, the power factor is unity. The average rms voltage among the three phases is 262Vwhilst the average rms current is 30 A.

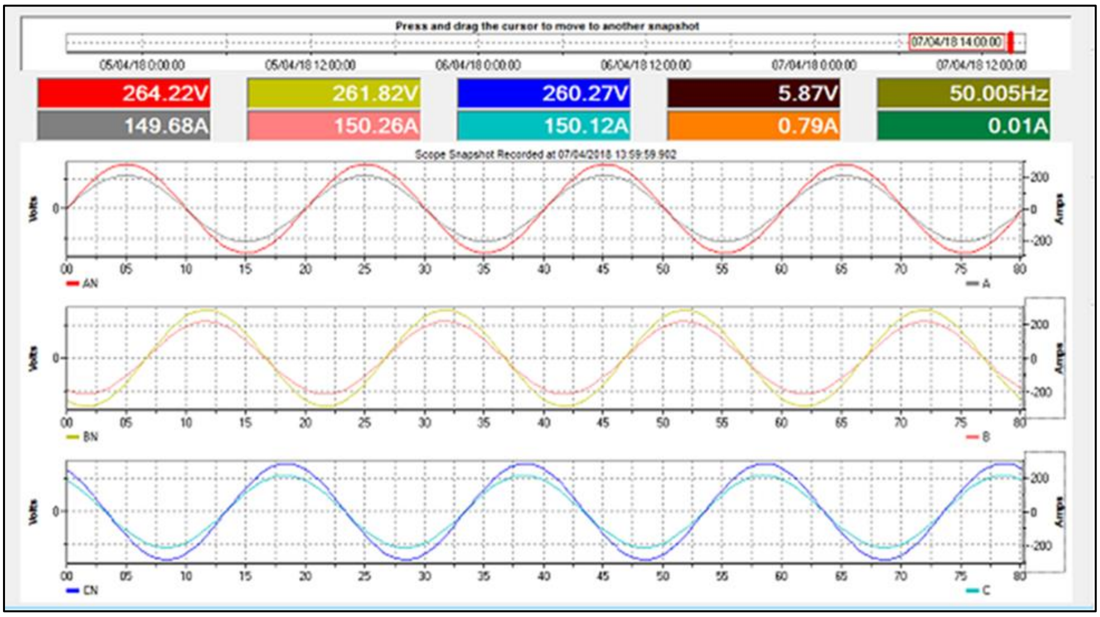


Figure 7. Output voltages and currents from site measurement of five units Zeverlution Pro 33K string inverters using Fluke 1750 power meter.

However, this measurement lack of input parameters. Input parameters can be determined by conducting MATLAB simulation. The input parameters can be determined by adjusting the parameters (in column A) gradually as stated in Table 3.

As can be seen from this table, the solar panel parameters have been gradually lowered in conjunction with the impedance (column B). In this process, as a start, the values in column E were determined from [2]. If after adjusting the impedance value, the outputs in column E failed to converge close to 262 V_{rms} and 30 A_{rms}, the values in column A will be lowered further. This process will only stop if the phase voltage and current in column E are close to 262 V_{rms} and 30 A_{rms} and also the $V_{DC} \approx 20*V_{mp}$ and $I_{DC} \approx 6*I_{mp}$.

3. Results and Discussion

Firstly, by observing Table 3**,** one can deduced that during the site measurement, the power produced by the solar panel string (120 panels connected together) was ≈ 17% lower than the power stated by the manufacturer in the datasheet. That is why the simulation result shows the input power is close to 25 kW.

Secondly, without incorporating the three-phase transformer at the output side, the output voltage and current will not achieve the targeted values as can be seen in column D. In column D, the phase voltage is very low if compared to the typical Malaysian transmission line phase voltage (240 V_{rms}).

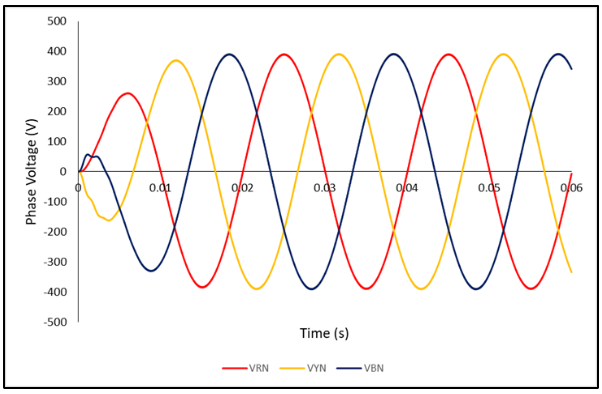
Journal of Physics: Conference Series **1432** (2020) 012029 doi:10.1088/1742-6596/1432/1/012029

So, without incorporating the three-phase transformer in the inverter design, it is impossible to achieve higher output voltage. The transformer ratio used for the simulation has 1.46 turns ratio. The result in Table 3 also shows that equation (1) is proven true.

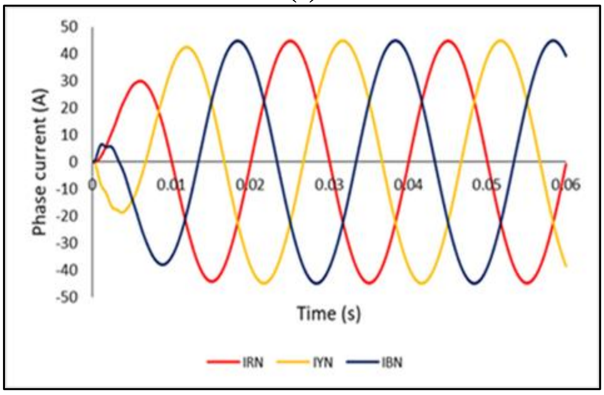
Table 3. Input and output parameters of the three-phase inverters

Solar panel parameters		Input Parameters			Output parameters		Output parameters (with 3 phase transformer)		
A	B	C			D		E		
V_{oc} = 37.6 V V_{mp} = 30.4 V I_{sc} = 8.81 A I_{mp} = 8.23 A 20*V_{mp} = 608 V 6*I_{mp} = 49.4 A	Z (Ω)	V_{DC} (V)	I_{DC} (A)	P (W)	V_{rms} (V)	I_{rms} (A)	V_{rms} (V)	I_{rms} (A)	P (W)
	4.00	609	49.3	30024	196	49.2	287.0	36.8	28981
	4.05	613	49.0	30000	198	49.0	289.1	37.0	29106
	4.10	616	48.7	29970	199	48.7	291.2	37.0	29102
	Solar panel parameters according to the datasheet [2]						Output parameters deviate hugely from the real measurement		
V_{oc} = 35.6 V V_{mp} = 28.8 V I_{sc} = 7.93 A I_{mp} = 7.41 A 20*V_{mp} = 576 V 6*I_{mp} = 44.5 A	Z (Ω)	V_{DC} (V)	I_{DC} (A)	P (W)	V_{rms} (V)	I_{rms} (A)	V_{rms} (V)	I_{rms} (A)	P (W)
	4.00	561	45.4	25460	181	45.3	264.3	31.2	24576
	4.05	565	45.2	25520	180	45.2	263.3	31.1	24442
	4.10	569	45.0	25570	184	45.0	268.5	31.5	24804
V_{oc} = 34.6 V V_{mp}= 27.9 V I_{sc} = 7.93 A I_{mp} = 7.41 A 20*V_{mp} = 558 V 6*I_{mp} = 44.5 A	Z (Ω)	V_{DC} (V)	I_{DC} (A)	P (W)	V_{rms} (V)	I_{rms} (A)	V_{rms} (V)	I_{rms} (A)	P (W)
	4.00	554	44.8	24790	179	44.7	260.9	30.4	23956
	4.05	557	44.6	24810	180	44.4	262.7	30.5	23965
	4.10	560	44.3	24800	181	44.1	264.3	30.5	23962
	The real solar panel parameters						Output parameters close To the site measurement		

Figure 8(a) and (b)show the simulation results of AC output voltage and current for the red, yellow and blue phases. Obviously, from these two figures, one can see that the alternating currents and voltages produced are in pure sinusoidal form. The amplitudes of the voltages are 371.5 V. For the phase currents, the amplitudes are 43.1 V. The phase angle between the voltages and their respective currents is zero degree. Meaning, the power factor equals to unity. Figure 8(a)and Figure 8(b)also show the 'disturbance' at the beginning of the sinusoidal waveforms. This phenomenon could be caused by the presence of the inductors and the capacitors in the circuit.



(a)



(b)

Figure 8. (a)Three-phase AC output voltage (b) Three-phase AC output current

4. Conclusion

This paper has presented the design and simulation of a 30 kW three-phase string inverter. The result has shown that, the true input power to the inverter is 24810 Watt, which is ≈ 17% lower than the values provided by the manufacturer. To match the values obtained from the site measurement, the DC input voltage and current were found to be 557 V and 44.6 A respectively.

This works has also shown that the pulse width modulation (PWM) technique in a three-phase inverter needs transformer to step up the output voltage to the intended level. However, by using PWM, the filtering of the unwanted harmonics is easy to implement with LC filter.

Acknowledgments
The authors would like to acknowledge School of Electrical System Engineering, Universiti Malaysia Perlis for the funding of this work.

References

[1] Yu Media Group. Kuala Perlis, Malaysia - Detailed climate information and monthly weather forecast [Internet]. Weather Atlas. [cited 2019Sep10]. Available from: https://www.weather-my.com/en/malaysia/kuala-perlis-climate

[2] Products [Internet]. Jinko Solar. [cited 2019Sep10]. Available from: https://jinkosolar.com/us/products/

[3] Rashid M., Kumar N and Kulkarni A 2014 Power Electronics: Devices, Circuits, and Applications (Boston: Pearson).

[4] Nilsson J W and Riedel S A 2015 Electric Circuits (New Jersey: Pearson)

[5] Sadiku A 2009 Fundamentals of Electric Circuits (New York: McGraw-Hill).

[6] Sahoo S K, Ramulu A, Batta S and Duggal S 2012 IET Chennai 3rd International on Sustainable Energy and Intelligent Systems (SEISCON 2012) (Tiruchengode, India) (IEEE Explore)

[7] Laali S, Abbaszadeh K and Lesani H 2010 International Conference on Electrical Machines and Systems (Incheon, South Korea) (IEEE Explore)

[8] Electrical Engineering - Power Electronics [Internet]. NPTEL. [cited 2019Sep10]. Available from: https://nptel.ac.in/courses/108105066

[9] Hart D W 2010 Power Electronics (New Jersey:Pearson)