Estimation of Optimum Tilt Angles of Grid-Tied PV Solar System via PVsyst Program in Baghdad-Iraq

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Abstract

The current system is the grid-tied PV solar system. CIGS is the thin film technology (Second Generation). The acronym of CIGS PV solar module comes from: Copper Indium Gallium Selenide. The system which is simulated to find the performance, optimum tilt and orientation angles is 5 kWp CIGS PV Solar system installed at al Mansour Company, Iraq-Baghdad (Latitude 33.3 º N, Longitude 44.4 º E and 34 meters above the Sea level). In this work is determined the amount of electrical energy generated, solar irradiation and performance ratio by PVsyst simulation program through changing the orientation (Azimuth Angle) toward the East, West and South. The optimum tilt angles and performance ratio (PR) when the monthly adjustment is used are (45º-55º) and 87.5% respectively for January, February, November and December, while (30º-33º) and 84.5% respectively for the march, April, September and October, (0º-15º) and 80.8% respectively for May, June, July and august. The optimum tilt angles when the seasonal adjustment is used are 15o for the summer season and 45º for the winter season. In the terms of the optimum fixed angle throughout the year, the optimum fixed tilt angle is 30º. The optimum azimuth angle is (0) where the loss/opt is zero.

Keywords: Optimum Angle, Simulation Program, Azimuth Angle, Tilt Angle and Performance Ratio.

حساب زوايا الميل المثلى للنظام الشمسي الكهروضوئي المرتبط تزامنيا مع الشبكة الوطنية الكهربائية في مدينة بغداد بوساطة برنامج المحاكاة PVsyst

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الخلاصة

النظام الحالي هو نظام كهروضوئي مرتبط بالشبكة الكهربائية العامة. CIGS هو تقنية الأغشية الرقيقة من الخلايا الشمسية (الجيل الثاني). المصطلح CIGS اختصار لـ: النحاس- الإنديوم الغاليوم- سيلينيد. النظام الذي تمت محاكاته لحساب الأداء، وزوايا الإمالة والتوجيه الامثلين هو نظام الطاقة الشمسية الكهروضوئية بسعة 5 kWp منصوب في شركة المنصور، العراق-بغداد (خط العرض 33.3º، خط الطول 44.4º و41 متر فوق مستوى سطح البحر). في هذا العمل بالإضافة الى تحديد الزوايا المثلى، تم تحديد مقدار الطاقة الكهربائية المتولدة، كمية الإشعاع الشمسي ونسبة الأداء بواسطة برنامج المحاكاة PVsyst من خلال تغيير الاتجاه (زاوية السمت الشمسي) نحو الشرق والغرب والجنوب. زوايا الميل المثلى ونسبة الأداء (PR) عند استخدام الضبط الشهري هي (45º-55º) و87.5% على التوالي لشهر يناير وفبراير ونوفمبر وديسمبر، بينما (30º-33º) و84.5% على التوالي لشهر مارس وسبتمبر وأكتوبر على التوالي، (0º-15º) و80.8% على التوالي لشهر مايو ويونيو ويوليو وأغسطس. زوايا الميل المثلى عند استخدام الضبط الموسمي هي 15 درجة لموسم الصيف و45 درجة لموسم الشتاء. فيما يتعلق بالزاوية الثابتة المثلى على مدار العام، فإن زاوية الميل المثلى الثابتة هي 30º زاوية السمت المثلى هي (0).

الكلمات المفتاحية: الزاوية المثلى، برنامج المحاكاة، زاوية السمت الشمسي، زاوية الميل ونسبة الأداء.

Introduction

PV solar technology is the most promising clean energy. Determine the optimum tilt angle is the fundamental principle in PV solar system installations to get the maximum possible energy output. PV solar systems can be installed on the rooftops, airplanes and satellites. PV solar system tilt angle adjustment is achieved either monthly or yearly. There is one tilt angle in the yearly adjustment, while there are several tilt angles in the monthly adjustment. PV solar system installation depends on the region of latitude. PV solar module is made from semiconductor materials and directly converts the solar radiation to electrical energy (George and Anto, 2012). PV solar modules should be placed at an optimum tilt angle to get the highest possible power from PV solar modules. The solar radiation amount that incidence on the PV solar module depends on the longitude and latitude of the site where the PV solar module is installed. While solar radiation incidences with the largest angle at mid-noon, it incidences the smallest angle in the mornings. So that the PV solar modules tilt angle varies annually, seasonally and monthly depending on regions (Handoyo and Ichsani, 2013) and (Rouholamini, *et al*., 2013). To obtain maximum solar radiation amount by PV solar modules, it requires to install these modules perpendicularly to the solar radiation where this exhortation applies to any module collect solar radiation from the sun like photovoltaic, solar cooker and solar hot water, etc. The PV solar modules can gain energy by 40% in summer to 10% in winter by tracking the sun movement, compare with fixed modules. In the northern hemisphere, the general rule for solar panel placement is, solar panels should face true south and in the southern, true nort (Pavlović, *et al*., 2010). This study is achieved by changing the orientation (Azimuth Angle) toward East, South and West for the angles (0º, 5º, 10º ,20º,30º, -5º, -10º, -20º and -30º) for completely system, the tilt angle is also changing for the following angles: (0º,10º,15º, 30º, 33º, 45º, 55º, 65º and 90º). In this manuscript, tilt angles of PV solar modules are estimated monthly and seasonal then they are compared with measured results conducted through the year entirely. PVsyst program is a PC software package that is used for data analysis, sizing and studying of completed PV solar systems. PVsyst deals with DC-grid systems, grid-tied systems, stand-alone systems and pumping systems. It comprises spacious meteorological databases, PV solar systems components databases and additional to the general of solar energy tools. The version of the PVsyst software package used in this study is 6.5.1 (Duffie and Beckham, 2006).

Equations of Tilt and Azimuth Angles Finding the Tilt Angle Equation

Baghdad is sited at latitude 33.3°N, longitude 44.4°E and 34 meters above sea level (Messenger and Ventre, 2003) and (Kasim, *et al*., 2020). Tilt angle depends on location and time, i.e., in each site, there are several tilt angles through the time of year. To estimate the tilt and azimuth angles to any position and time through year, the equations from 1 to 7 must be used. The goal of this manuscript is to estimate the amount of energy output, performance ratio and solar insolation to the PV solar system by PVsyst software.

$$AST = LST + (4\text{min/deg})\,(LSTM - Long) + ET \quad (1)$$

Where: AST is Apparent Solar Time, LST is Local Standard Time, LSTM is Local Standard Time Meridian, ET is Equation of Time and long is Longitude.

$$LSTM = 15^{\circ} * (long/15) \quad (2)$$

$$ET = 9.87 \sin(2B) - 7.53 \cos(B) - 1.5 \sin(B) \quad (3)$$

Where, B= (360/365) *(d−81) …………….. (4)
(Zerubavel, 1982) and (Karafil, *et al.*, 2015).

Hour Angle (ω) is the angle between the longitude of the location and the longitude of sun lights. The angle before noon is negative and afternoon is positive, becomes 90º in sunrise and sunset while it is 0º at midday. Hour angle is given in equation 5. The hour angle increases by 15 degrees every hour. It follows that at local noon, the hour angle is zero: (0 < t < 24, then t = 12 at local noon, t = 6.5 at five and one-half hours before local noon and t = 18.25 at six and one-quarter hours after local noon), we have that at time to, the measure of the hour angle is (Patko, *et al.*, 2013) (Despotovic and Nedic, 2015).

$$\omega = 15\,(to - 12°) \text{ .... (5)}$$

Declination Angle (δ) is the angle between the sunbeams and the equator line. It is negative in the southern hemisphere and positive in the northern hemisphere, it contrasts between (-23.45º ≤ δ ≤ 23.45º). It at peak point on 21 June (23.45º) while at the minimum point (-23.45º) on 22 December in winter. The declination angle is demonstrated in Fig (1).

$$\delta = 23.45° \sin\left[\frac{n+284}{365} \times 360°\right] \text{ …….. (6)}$$

Where: n is the day number in the year, and 1 January is the beginning (Patko, *et al.*, 2013), (Darhmaoui and Lahjouji, 2013) and (Stine and Geyer, 2015).

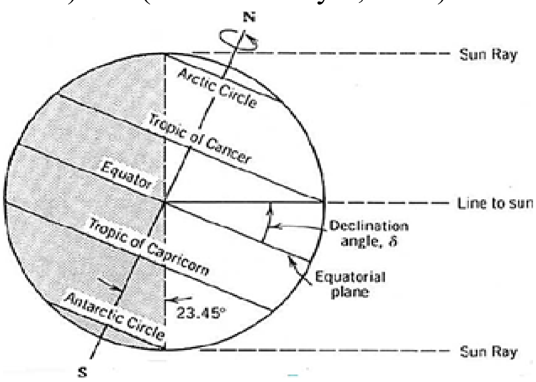

Figure (1) Declination Angle.

Tilt Angle (βz) is given in equation 7:

$$\beta z = |\phi - \delta| \text{ .... (7)}$$

Where ϕ = Latitude

Finding the Azimuth Angle Equation

Solar Azimuth Angle (γ_s) is the angle between the direct solar radiation and the geographical due south. This angle is (+) from south to west and (-) from south to east. (γ_s) is 180º at midday and it is the complement of the zenith angle. The azimuth angle is given in equation 10 (Patko, *et al.*, 2013) and (Messenger and Ventre, 2003).

Zenith Angle (θ_z) is defined as the angle between the sunlight and the perpendicular axis. Zenith and azimuth angles are presented in Fig (2). Zenith angle is given by equation 8 (Messenger and Ventre, 2003) and (Patko, *et al.*, 2013 2013). Zenith angle is estimated based on the other angles (Kaldellis and Zafirakis, 2012) and (Patko, *et al.*, 2013 2013).

$$\theta_z = \cos^{-1}(\cos(\phi)\cos(\delta)\cos(\omega) + \sin(\phi)\sin(\delta)) \text{ .... (8)}$$

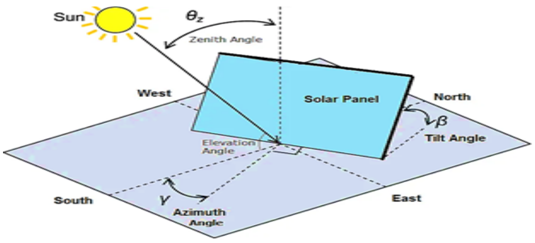

Figure (2) Tilt and Azimuth Angle.

Solar Elevation Angle (α) is the angle between the horizontal plane and the sunbeam. This angle is the complement of the zenith angle. The elevation angle is given by the following relation:

$$\alpha = \sin^{-1}[\cos(\phi) * \cos(\delta) * \cos(\omega)] + [\sin(\phi) * \sin(\delta)] \text{ …………………….. (9)}$$

So, the azimuth angle is given as follow:

$$\gamma = \cos^{-1}\left[\frac{\sin(\alpha).\sin(\phi) - \sin(\delta)}{\cos(\alpha)\cos(\phi)}\right] \text{ ……. (10)}$$

Results and Discussion

Optimal Tilt Angles Determine to PV Solar System in Baghdad City

Monthly Adjustment of Optimal Tilt Angles at Zero Azimuth Angle

The current study depends on the results of PVsyst software and real measured data. PVsyst simulation program is a clear sky model, where it does not affect the atmospheric conditions as dust, rain and cloud, so that the effect of the tilt angles seems obvious.

Optimal Tilt Angles in January and February

The sun angle is the lowest in January and February among other months, so the solar radiation is also the lowest. Consequently, the energy output of the PV solar modules is the lowest. To obtain the largest amount of solar radiation must be adjusting the PV solar module in angle to obtain the largest amount of solar radiation to obtain the maximum amount of electric energy. The optimum tilt angles in January and February are 45^o and 55^o as shown in Table (1).

Optimal Tilt Angles of March and April

The sun angle is higher in March and April than in January and February, therefore the optimal tilt angle is 30^o or 33^o as shown in Table (2).

Optimal Tilt Angles in May and June

The optimum tilt angles in the months of May and June are (0^o, or 3^o, or 5^o, or10^o, or 15^o) (from 0^o to 15^o), any tilt angle from these which are between two brackets can be used as illustrated in Table (3).

Optimal Tilt Angles in July and August

Since the sun angle is the highest in June July and August, the optimal tilt angles in these months (July and August) range from 0^o to 15^o, as shown in Table (4).

Table (1) The Optimal Tilt Angles in January and February.

January	S.IR	E.P	PR	February	S.IR	E.P	PR
0 Degree	84	359	86.4	0 Degree	101.2	435	86.9
3 Degree	89.0	383	87	3 Degree	105.6	456	87.1
5 Degree	92.2	399	87.3	5 Degree	108.5	469	87.3
10 Degree	99.9	435	88	10 Degree	115.0	499	87.6
15 Degree	107.0	468	88.4	15 Degree	120.9	525	87.8
30 Degree	124.1	544	88.7	30 Degree	134	582	87.8
33 Degree	126.7	555	88.5	33 Degree	135.8	589	87.7
45 Degree	134.1	584	88	45 Degree	139.7	605	87.5
55 Degree	136.5	593	87.8	55 Degree	139.1	603	87.6
65 Degree	135.4	589	87.9	65 Degree	135.0	587	87.8
90 Degree	117.7	518	88.9	90 Degree	110.7	480	87.7

Table (2) The Optimal Tilt Angles in March and April.

March	S.IR	E.P	PR	April	S.IR	E.P	PR
0 Degree	148.5	631	85.9	0 Degree	169.1	711	84.9
3 Degree	152.8	650	85.9	3 Degree	171.6	721	84.8
5 Degree	155.5	662	86	5 Degree	173.0	726	84.8
10 Degree	161.6	688	86	10 Degree	176.0	738	84.8
15 Degree	166.6	709	86	15 Degree	177.9	745	84.7
30 Degree	175.7	745	85.6	30 Degree	177.2	741	84.5
33 Degree	176.4	747	85.6	33 Degree	176.0	736	84.5
45 Degree	175.2	742	85.6	45 Degree	167.3	701	84.6
55 Degree	169.4	720	85.8	55 Degree	155.8	653	84.7
65 Degree	159.5	680	86	65 Degree	140.8	589	84.5
90 Degree	119.1	500	84.8	90 Degree	91.8	368	81.1

Table (3) The Optimal Tilt Angles in May and June.

May	S.IR	E.P	PR	June	S.IR	E.P	PR
0 Degree	197.7	811	82.9	0 Degree	213.0	858	81.4
3 Degree	198.8	815	82.8	3 Degree	213.3	859	81.3
5 Degree	199.2	817	82.8	5 Degree	213.3	858	81.3
10 Degree	199.6	818	82.8	10 Degree	212.3	854	81.2
15 Degree	198.8	814	82.7	15 Degree	210.0	845	81.3
30 Degree	189.5	776	82.7	30 Degree	196.8	791	81.2
33 Degree	186.4	763	82.7	33 Degree	192.8	775	81.2
45 Degree	170.4	697	82.6	45 Degree	173.0	694	81.0
55 Degree	153.0	626	82.6	55 Degree	152.9	613	80.9
65 Degree	133.1	540	819	65 Degree	130.0	514	79.9
90 Degree	74.2	280	76.3	90 Degree	64.8	232	72.4

Table (4) The Optimal Tilt Angle in July and August.

July	S.IR	E.P	PR	August	S.IR	E.P	PR
0 Degree	216.0	861	80.5	0 Degree	201.6	806	80.8
3 Degree	216.8	863	80.5	3 Degree	204.0	815	80.7
5 Degree	217.0	864	80.4	5 Degree	205.3	820	80.7
10 Degree	216.8	863	80.4	10 Degree	207.8	829	80.6
15 Degree	215.2	856	80.4	15 Degree	209.0	833	80.6
30 Degree	203.2	808	80.3	30 Degree	204.9	817	80.5
33 Degree	199.5	793	80.3	33 Degree	202.7	808	80.5
45 Degree	180.4	717	80.2	45 Degree	189.7	756	80.5
55 Degree	160.5	636	80.1	55 Degree	173.9	693	80.5
65 Degree	137.6	540	79.3	65 Degree	154.3	613	80.3
90 Degree	71.6	258	72.7	90 Degree	92.6	348	75.9

Optimal Tilt Angle in September and October

Since the sun angle in September and October is lower than July and August, the optimum tilt angle is 33^o for (September and October). The tilt angle of 45^o can also be used for October, as shown in Table (5).

Optimal Tilt Angle in November and December

The optimum tilt angle in November and December is 55º because the sun angle is the lowest in these months, as shown in Table (6).

Monthly Optimal Tilt Angles Summary (MOTA)

In this state there are solely five optimal tilt angles during the year which are (45 º, 50º, 30º, 33º, and 15º) as shown in Table (7).

Optimal Tilt Angle Seasonal Adjustment

In a seasonal adjustment state, the tilt angle is changed twice during the year to obtain two optimal tilt angles for all the year months. In this state the year is separated into two portions: one for summer (April, May, June, July, August and September) and the other for winter (October, November, December, January and February). For each portion of the year the optimal tilt angle is determined. Ten angles are simulated to determine which two are ideal tilt angles (one for Winter and the other for Summer). The tilt angles are selected as follows: (9º and 44º, 10º and 55º, 10º and 45º, 15º and 45º, 15º and 55º for Summer and Winter Respectively). Table (8) shows that the (15º for Summer and 45º for Winter) are the optimal tilt angles, as the tilt angles of the PV solar modules are adjusted twice during the year.

Table (5) The Optimal Tilt Angle of September and October.

September	S.IR	E.P	PR	October	S.IR	E.P	PR
0 Degree	172.7	702	82.1	0 Degree	130.3	539	83.5
3 Degree	177.0	719	82.1	3 Degree	135.2	560	83.6
5 Degree	179.7	730	82.1	5 Degree	138.2	573	83.7
10 Degree	185.6	754	82.1	10 Degree	145.3	604	83.9
15 Degree	190.4	773	82.0	15 Degree	151.5	630	84.0
30 Degree	197.4	799	81.8	30 Degree	164.5	685	84.2
33 Degree	197.4	800	81.8	33 Degree	166.0	692	84.2
45 Degree	193.1	783	81.9	45 Degree	168.4	702	84.2
55 Degree	184.2	748	82.0	55 Degree	165.8	692	84.3
65 Degree	170.7	693	82.0	65 Degree	159.2	665	84.4
90 Degree	119.9	475	80.1	90 Degree	126.2	523	83.7

Table (6) The Optimal Tilt Angle in November and December.

November	S.IR	E.P	PR	December	S.IR	E.P	PR
0 Degree	97.1	411	85.4	0 Degree	77.9	330	85.6
3 Degree	102.7	436	85.8	3 Degree	82.8	354	86.3
5 Degree	106.3	453	86.1	5 Degree	86.0	369	86.7
10 Degree	114.8	492	86.6	10 Degree	93.5	405	87.5
15 Degree	122.6	528	87	15 Degree	100.5	438	88
30 Degree	141.2	610	87.3	30 Degree	117.6	516	88.6
33 Degree	143.9	622	87.3	33 Degree	120.3	527	88.5
45 Degree	151.7	654	87.1	45 Degree	128.1	559	88.2
55 Degree	153.8	663	87.1	55 Degree	131.0	570	87.9
65 Degree	152.0	656	87.2	65 Degree	130.5	568	88
90 Degree	130.7	565	87.4	90 Degree	115.0	504	88.6

Table (7) The Summary of Monthly Optimum Tilt Angles.

Month	Simulated OTA	Simulated S.IR	Simulated E.P	Simulated PR %	Calculated PR% [13]	Calculated OTA [12]
January	45-55 Degree	136.5	593	87.8	81.7	45-60
February	45-55 Degree	139.1	603	87.6	82.7	45-60
March	30-33 Degree	175.7	745	85.6	83.7	30
April	30-33 Degree	177.2	741	84.5	82.5	30
May	0-15 Degree	199.6	818	82.8	79.3	15
June	0-15 Degree	212.3	854	81.2	77.4	15
July	0-15 Degree	216.8	863	80.4	76.5	15
August	0-15 Degree	207.8	829	80.6	78.8	15
September	30-33 Degree	197.4	800	81.8	80	15
October	30-33 Degree	168.4	702	84.2	80.8	30
November	45-55 Degree	153.8	663	87.1	81	44-60
December	45-55 Degree	131.0	570	87.9	81.2	45-60
Sum		2115.6	8781	84.3	80.5	Average

Table (8) Seasonal Adjustment of the Optimal Tilt Angles.

OTA	Sum of S.IR	Sum of E.P	Average of PR %
9 and 44 Degree	2092.5	8691	83.9
10 and 45 Degree	2095.1	8702	83.9
10 and 55 Degree	2093.7	8696	83.9
15 and 45 Degree	2098.3	8713	83.9
15 and 55 Degree	2096.9	8708	83.9

Fixed Optimal Tilt Angle

When the frame of the solar PV module is fixed, there is only one option to choose the optimum tilt angle, that is, only one tilt angle should be chosen throughout the year. PVsyst program results show that the fixed optimal tilt angle is 30º, Figure (4) proves that. Figure (3) represents the losses caused by PV solar modules installation. This Figure shows there are no losses when installing the PV solar modules at a tilt angle of 30º and orientation angle of zero. Table (9) represents the values of the solar irradiation (S.IR), energy produced (E.P) and the average performance ratio (PR) when selecting the title angle 30º as a fixed tilt angle throughout the year.

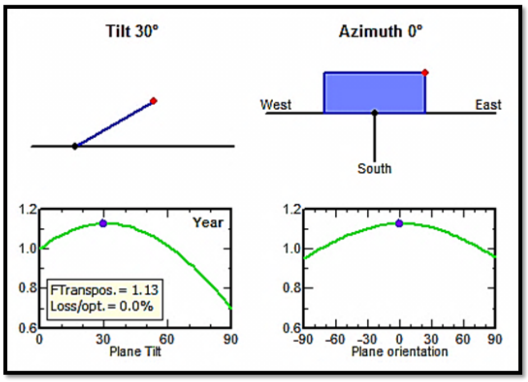

Figure (3) Optimum Fixed Angle.

Determine the Optimal Azimuth Angle

Outcomes of PVsyst program show that the (0) azimuth angle is the optimal azimuth angle (Orientation Angle) for solar modules, where (0) azimuth angle is toward the exact south. The azimuth angles that are selected of (0º, 5º, 10º, 20º, 30º, -5º, -10º, -20º and -30º), where the minus signal denotes the western orientation, while the plus signal denotes the eastern orientation. Figures (3) and (4) display that the zero angle is the optimal azimuth (Orientation) angle. Figure (4) shows all the selected azimuth angles and their losses, where there are no losses at the zero-azimuth angle.

Study of Azimuth Angles

Different azimuth angles are simulated to find the optimal azimuth angle as illustrated in Table (10). This study includes the effect of the deflection from the south exact (0º) on the solar insolation and energy output. The results in Table (10) demonstrate that the deflection from 0º until +/-30º hasn't large effect on the energy production, where the loss with respect to optimal azimuth angle (0º) is (0.0%). While the losses caused by the deflection in (5º and -5º, 10º and -10º) can be neglected and losses caused by deflection in (20º and -20º) also can be neglected because these losses are solely (1%-0.88%) and equal 6.3 kWh/month, when the monthly energy output is 693.5 kWh. Even azimuth angles deflected in +/-30º haven't significant effect on energy output, where the loss with respect to optimal azimuth angle (0º) is (1.8%-2.0%).

Table (9) Fixed Optimal Tilt Angle (FOTA).

FOTA	Sum of S.IR	Sum of E.P	Average of PR %
Fixed Angle (30º)	2026.1	8415	83.9

Table (10) Comparison between Different Azimuth Angles.

Azimuth Angle	Loss/opt	Sum. S.I/year	Sum. E.P/year	PR/year
0 Degree	0	2026.1	8415	83.9
5 Degree	-0.08%	2025	8408	83.9
-5 Degree	-0.1%	2024	8406.6	83.9
10 Degree	-0.23%	2021.3	8395.6	83.9
-10 Degree	-0.3%	2019.1	8389	83.9
20 Degree	-0.88%	2008.2	8340	83.8
-20 Degree	-1%	2005.3	8322	84
30 Degree	-2.1%	1986.9	8238.3	83.8
-30 Degree	-2.25%	1980.1	8238.3	84.1

Where: loss/opt is the ratio of loss to optimum, S.I is the solar irradiation, E.P is the energy produced and PR is the performance ratio.

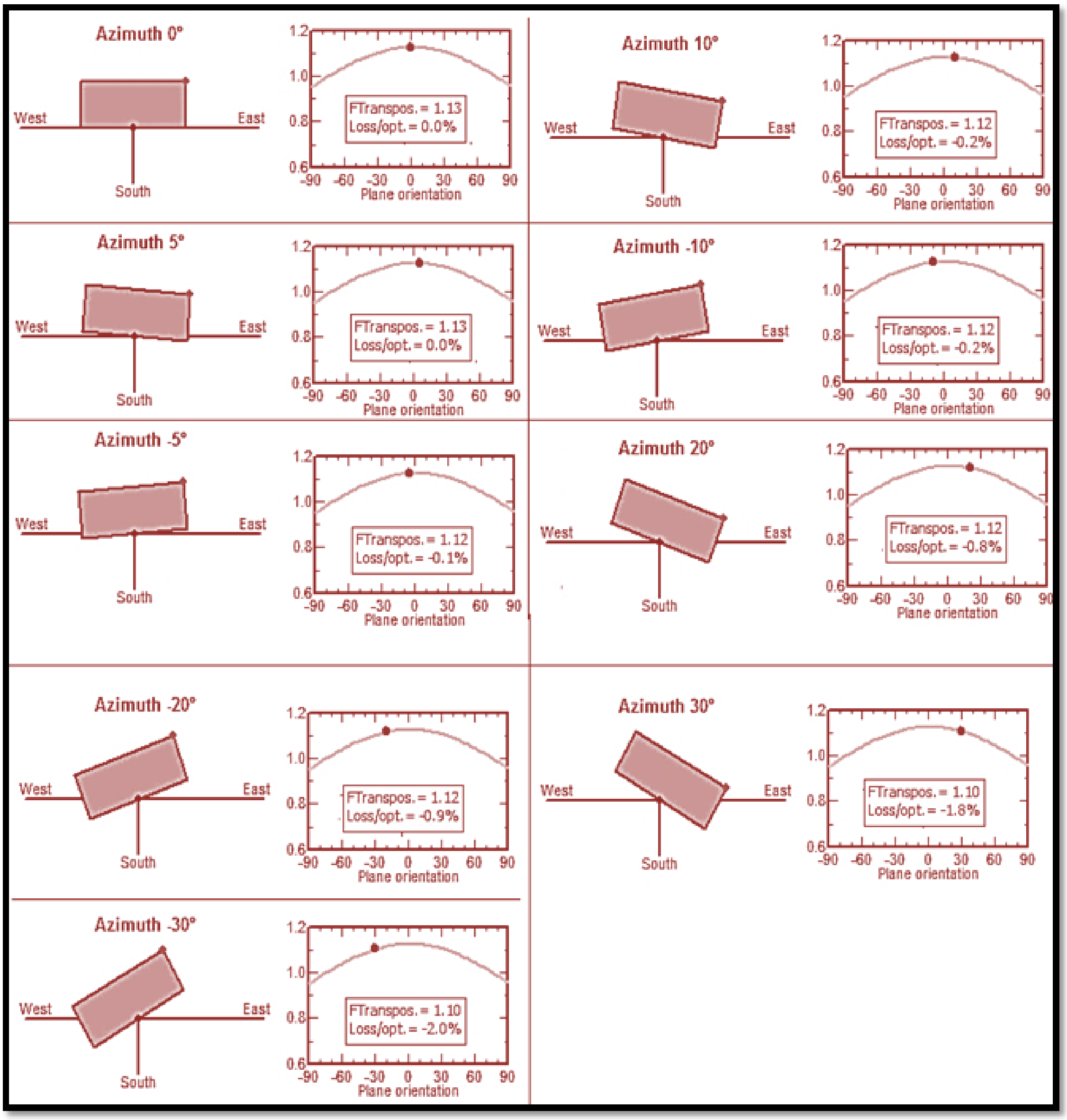

Figure (4) Azimuth Angles.

Conclusions

The study of the tilt angles in PVsyst software clearly exhibits the relationship between PV solar modules and solar radiation because this simulation program is not affected by the atmospheric conditions.

Since there is not a large difference between seasonal and monthly tilt angles, it is best to choose seasonal adjustment of tilt angles because it is easier than a monthly adjustment.

There is not a large difference among fixed, monthly and seasonal adjustment of tilt angle consequently, fixed adjustment can be chosen.

The optimal azimuth angle is zero, but this angle can be oriented until -/+20º or even -/+30º in cases of compulsion, as shown in Table (10).

There is a small difference in performance ratio (PR) when tilt and azimuth angles are changed, this means the performance ratio doesn't depend on the azimuth and tilt angles.

There is small difference between simulated and real calculated values

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