SPS 2000 Demonstration of Energy Reception by Microwave Rectennas in Malaysia

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Abstract- As the worlds' population increases, the demand for energy, particularly electrical energy also increases. However, due to the depletion of energy in particular the hydrocarbons with time, an alternative sources is needed. Solar energy is one of the safest to be explored. This paper presents an approach in using solar power to generate electrical energy in the future using an SPS 2000 (Solar Power Satellite) rectenna. The suitable location of the rectenna in Malaysia has been identified. Spherical rectenna is chosen for optimized reception area and for ease of analysis. The amount of energy received by this rectenna is simulated using Visual Basic V.5.0. The latitude of the rectenna, rectenna radius, earth inclination, distance between rectenna and satellite and the time of the year of inception determine energy reception. The program also estimates the price per kWh of energy generated. However, this is not the real of electricity as the satellite and the transmitting costs were not considered in the calculation.

Keywords
Solar, energy, inclination, inception, rectenna.

I. INTRODUCTION

We are living at a time when there is a greater awareness of the energy problems. Including the growth in energy consumption, the question that most probably will come across the energy planners in all over the world is "How can we best supply humanity's growing energy needs with less impact on the environment". Up till now there is still no clear alternatives of energy sources replacement, as there is a limit to our reserves of fossil fuel. In addition, a total dependence on fossil fuel is not the answer since burning coal, oil and gas will raise the risk of global climate change, as they will pour carbon dioxide into the atmosphere. While the nuclear fusion reactors avoid the greenhouse problem but introduce a new problem of disposing the nuclear waste. Another alternative of energy sources is water, which can produce hydroelectric power. But to generate hydropower will require a large scale of land that will significantly disrupted ecosystem and human habitats. Due to the fact, this paper explores the possibility of solar power to generate electrical energy in the future using an SPS 2000(Solar Power Satellite) rectenna, since solar energy is one of the safest to be explored.

The rest of the paper is organized as follows. Section 2, briefly describes the background of the solar power satellite approaches and also the research methodology of this work. Section 3 contains a brief description on the theory and the mathematical equation for prediction the energy projected by SPS 2000 rectenna. The simulation results are discussed in section 4. Finally, section 5 contains the conclusions and an outline of future work. Lastly, the references are placed on the section 6.

II. LITERATURE REVIEW

The system functional model of SPS2000 is presented in Figure 1. P.collin and H Matsuoka proposed in [1] 4 main components to generate electricity from space: a large satellite, a rectifying antenna (rectenna), control and storage system and a power distribution system.

A large satellite containing a huge amount of solar cell modules is required to gather the solar energy from sun. This collected energy is converted to electric energy (dc) by the solar cells. The electric energy is then converted to a high power microwave beam at 2.45 GHz and transmitted from space to earth. The SPS 2000 satellite is being planned to orbit above the equator at an altitude 1100km, from where it would transmit a10 MW beam of microwave energy to the number of microwave power receiving antennas (rectennas) sited near the equator [2]. The microwave bean transmitted from the satellite antenna will be able to move through an angle of +/-30 degrees to the vertical in the west-east plane, and so rectennas should generally be separated by some 1200 km from west to east in order to receive power for the longest possible time.

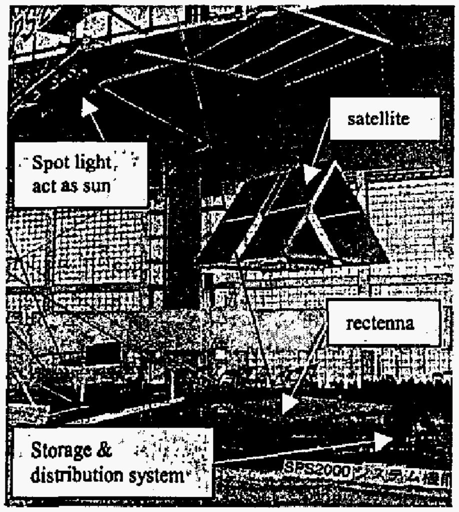

Fig. 1. The system functional model of SPS 2000

On earth a rectifying antenna or rectenna situated in an equatorial country is positioned to receive the microwave beam. Each rectenna will have an area of up to 1-2 square km, and will generate electricity from the satellite's intermittent transmissions. Due to the distance, the received signal is low in power density. This signal is then re-converted to electrical energy (dc) and fed to electrical loads for storage. Due to the location of the satellite (1100km orbit)the rectenna will receive the signal for a specified time period (10MW@200s) each orbit. The beam will then be terminated by control mechanisms at the satellite and rectenna control, as the satellite is out-of-sight with the rectenna.

At the control and storage system, the signal is further processed to the required output level of the distribution system in the particular rural area the rectenna is serving and temporarily stored. Using energy storage it will be possible to provide a continuous electricity supply of 100 – 200 kW, or a greater out put for some fraction of the day.

The power produced by the rectenna will not only all be used up, it will vary accordingly to meet demand of the period of the day. For instant, electricity is heavily needed during night period or late evening for lighting, cooking and other recreational activities. But during the day many users will not necessarily needs lights. In order on the power output during the day of the SPS 2000 rectenna to be economically useful, it will be necessary to have a system of power storage to convert the intermittent output of the SPS 2000 satellite into power that is available to the users on demand.

System on the other hand process to ac and is finally distributed as continuous electricity for consumer use in the rural areas especially the stored electric power in the villages. It can also be appropriately interfaced to existing 3 phase lines for effective distribution.

III. THE THEORY OF ENERGY RECEPTION

For potential users of the energy to be produced by the SPS 2000 system, one of the most important parameter is the amount of electricity that will actually be available for user.

On present plans the SPS 2000 satellite is being designed to transmit 10MW of microwave energy in a narrow beam towards the earth. However, the actual amount of power transmitted will vary continuously as the distance and angel between the sun and the satellite solar panels changes, depending on the time of day, earth inclination, the distance between satellite and rectenna, the rectenna radius and the rectenna efficiency, on the rectenna attitude and on the season. Consequently the amount of microwave energy transmitted during each day will also vary.

The microwave beam strength will depend on the amount of solar radiation intercepted by the solar panels, which depends on the satellite's area perpendicular to the solar radiation. When the perpendicular to the base of the satellite is pointing radially away from the Sun, the area is taken as 1 Refer to Figure 2).

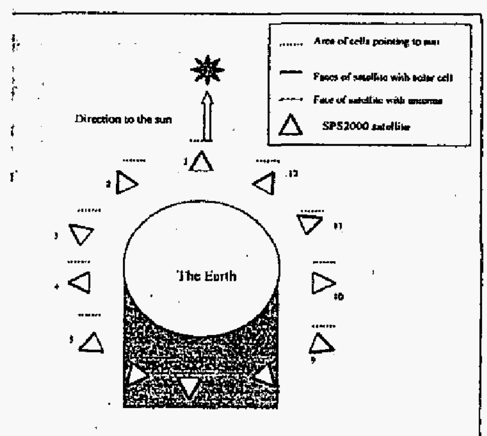

Fig. 2. Variation in area of solar cells facing the sun

Another major influence on the microwave beam intensity at the ground is the area over which it is spread. When the satellite is directly overhead (at a distance of 1100 km and angle between beam and horizontal of 90 degrees), the full beam on the ground is 1 km in radius. Consequently, the beam will spread over a wider area when the transmission distance is greater. In addition, when the angle between the satellite beam and the Earth's surface is not 90 degrees, the shape of the beam footprint on the ground is distorted from a circle into an ellipse. Another effect of the changing direction of the beam is due to the fact that the transmitting antenna is not steerable but fixed in a horizontal orientation. Thus, as the angle between the microwave beam and the vertical increases, the cross-sectional area of the antenna seen from the rectenna, decreases. This will cause the beam to be more strongly refracted at the antenna, thereby widening the beam and reducing the energy density further. The microwave power intensity pattern at rectenna is a perfect circle only at the midpoint

The further from the equator a rectenna is sited, the lower the average power intensity of the microwaves that it receives [3]. This is due to the increased distance and angle to the satellite causing the pattern of microwaves on the ground to cover a larger area than for a rectenna exactly on the equator, thereby reducing the average microwave intensity at the rectenna. The general equation of the factor with different latitude can be described as:

$$W_{lat} = Cos\,(lat * 10.94 * \pi/180) \quad (3.1)$$

Where W_{lat} is the factor with the different latitude and lat is the latitude of the rectenna site in degrees. $\pi/180$ is the coefficient value to change the degree value to radiant. The coefficient 10.94 is a mathematical factor value to show the effect of the latitude changes on Earth.

Total energy received is also can be influenced by the rectenna radius factor where the amount of power received increases with rectenna radius.

A. Summation of Energy Received

To develop the SPS 2000 rectenna system, the correct equation for the energy prediction must be proven. First of all, divide the rectenna into segments each 10 meter in radial extent and of angular width 22.5 degrees such as in Figure 3. Consequently, the outer regions of the rectenna are divided into larger segments then the inner regions.

The program takes one of the outer corners of each segment (point P) and converts its position in the rectenna to a position in the beam cross-section. The intensity at that point of the beam is then assumed to be the average intensity over the whole segment (area A) and the energy received is summed [3]. The efficiency of the rectenna conversion from microwave to DC power is provisionally assumed to be 80%.

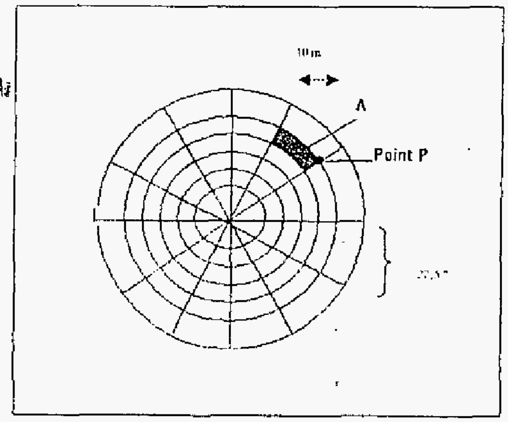

Fig. 3. Division of rectenna for summation of energy received.

Based on Figure 4, the determination of beam intensity, ρ depends on the size of rectenna area. The microwave intensity will become less compact at the edge of the beam footprint.The microwave intensity may be given as:

$$\rho = W/m^2 \quad (3.2)$$

Where ρ is the microwave intensity, W is the power and m^2 is the rectenna area.

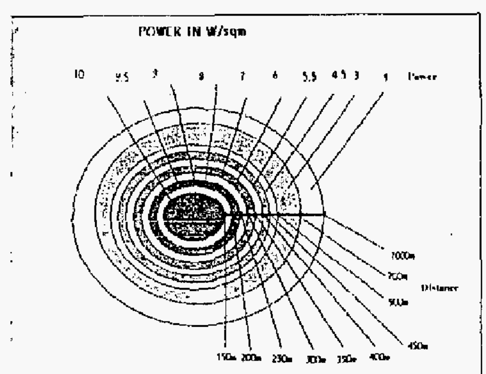

Fig. 4. Beam Intensity Profile At The Earth's surface

This allows the power received being represented as:

$$W = \rho(m^2)$$

Or,
$$P_r = \rho(A) \quad (3.3)$$
$$P_r = \rho(\pi r^2) \quad (3.4)$$

Where P_r is the power received which is measured in Watts, and A is the rectenna area in m^2 and r is the rectenna radius. Area of reception depends on the length of rectenna radius.

The earth follows an elliptical path around the sun, taking about a year for each cycle. The earth's axis is tilted at a constant angle of 23° 27' relative to the plane of rotation at all times.(angle of declination = 0 as reference). Based from this fact, the difference between power at maximum and minimum is a factor of Cos (23° 27'). When the angle of earth inclination is 23 ° 27', power can be received is at a minimum. This is because the distance between satellite and sun is further away.

The relation between received power and earth inclination through the year can be represented by the factor of power inclination. The factor of power inclination, $w_{incline}$ may be expressed as

$$w_{incline} = Cos\ (\theta°) \qquad (3.5)$$

Where $\theta°$ is the angle of earth's inclination. The determination of $\theta°$ is based on the satellite condition from the equator line. Hence, θ is assumed as

$$\theta° = 0° \qquad (3.6)$$

(power at maximum)

$$\theta° = 23°27' = 23.5° \qquad (3.7)$$

(power at minimum)

$$0° < \theta° < 23.5° \qquad (3.8)$$

(power between maximum and minimum)

B. Energy Per Pass

In SPS 2000 system, there are about 12-13 satellite passes in a day (including night-time passes when power is not delivered). Each pass will deliver different amount of energy. The difference is caused by the strength changes of the sun energy and the variation factor of distance and angle between satellite and sun.

Referring to the relations of (*3.1*), (*3.4*) and (*3.5*), the power during each pass can be computed as

$$P_n = \rho(A)(w_{lat})(w_{incline})$$
$$P_n = \rho(\pi r^2)(w_{lat})(w_{incline}) \qquad (3.9)$$

Hence, energy received for each pass

$$E_n = \rho_r(\pi r^2)(w_{lat})(w_{incline})(200/3600) \qquad (3.10)$$

Where n is pass ($1 \leq n \leq 13$) and 200/3600 is the time of pass. Satellite beam power only 200 second for each pass. ρ_r is beam intensity at r radius. Hence, the received energy during the day is

$$E_{day} = E_1 + E_2 + E_3 \ldots\ldots + \ldots + E_{13}$$

$$E_{day} = \sum E_n \qquad (3.11)$$

Where $\sum E$ is the summation of energy for all passes.

The total energy received during one year is estimated by multiplying the number of passes per year by the average amount of energy received during each pass. It can also be defined as

$$E_{year} = (n_{pass\_year})(Av_{energy\_year}) \qquad (3.12)$$

Where E_{year} is the total energy received during one year and n_{pass_year} is the number of passes for one year, or given as

$$n_{pass\_year} = (n_{day})(n_{averagepass}) \qquad (3.13)$$

And Av_{energy_year} is the average amount of energy received during each pass. It can also be expressed as

$$Av_{energy\_year} = (w_{incline})(w_{lat})(weight) \qquad (3.14)$$

Where n_{day} is the number of days in a year and $n_{averagepass}$ is the average pass in a day. $w_{incline}$ is the factor of earth inclination, w_{lat} is the latitude factor of rectenna site while *weighting* is given by

$$weight = [(0.8(energy_{oneday})(8.4)/9] / 12.4 \qquad (3.15)$$

Therefore,

$$weight = 0.06022(energy_{oneday}) \qquad (3.16)$$

Where 0.8 is the factor of rectenna conversion efficiency of 80%, 8.4 is the average passes during the day time and 9 is the number of passes during the day time. 12.4 is the average passes in the whole day.

Hence by putting (3.13) and 3.14) into (3.12), the energy received uring the first year can also be computed as

$$E_{year} = (n_{day})(n_{veragepass})(w_{incline})(w_{lat})(weight) \qquad (3.12)$$

Figure 5 show an example of the total solar cell area facing the sun for pass2 position base on figure 2.

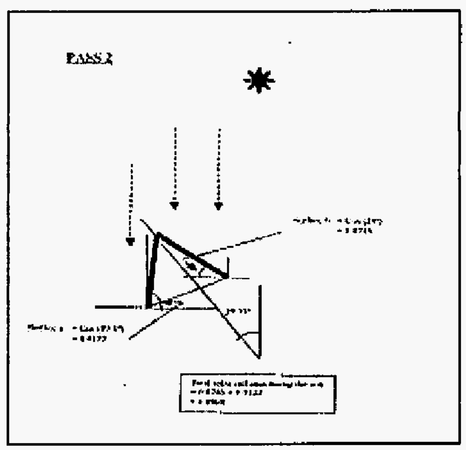

Fig. 5. Satellite position at Pass 2

IV. SIMULATION RESULTS AND DISCUSSION

Performance of many rectenna sites has been done on energy received of the rectenna at different sites, size, the different condition of power and the different for each satellite passes. Few improvements had been made, basically on the simulation program was designed using Visual Basic version 5.0 software. This software has the ability to calculate and estimate the energy that will be received by a rectenna of a given size at the given latitude, the amount of energy received in a day, the rate of the land use for each rectenna site, the average cost/kW of energy delivered during the first year and the value of power supply during the day and night.

Thus, by using the simulation, the influence of the distance and the angle between the satellite and the rectenna towards the microwave beam 'footprint' on the ground can be illustrated. The nearer rectenna site with larger radius, the energy can be received at maximum.

The analysis on different latitude for each rectenna sites is done based on the same rectenne size. The rectenna size is permanently assumed to be 500 meters in radius. The suitable rectenna sites had been chosen are equatorial line (0° latitude), Kuching, Sarawak (1° latitude), Skudai, Johor (1.1° latitude) and Pasir Gudang (1.42° latitude). The effect of the different satellite passes during the day, where there are about 13 passes in a day. Refer to Table 1 for the results.

Table 1. The results for different latitude with same radius

	EQUATORIAL		KUCHING		SKUDAI		PASIR GUDANG	
Latitude	0 degree		1.0 degree		1.1 degree		1.42 degree	
Radius	500 meters		500 meters		500 meters		500 meters	
	Power Max (kWh)	Power Min (kWh)	Power Max (kWh)	Power Min (kWh)	Power Max (kWh)	Power Min (kWh)	Power Max (kWh)	Power Min (kWh)
Pass 1	196.349	180.044	192.77	176.789	192.03	176.104	189.1719	173.482
Pass 2	179.24	159.789	171.071	156.883	170.409	156.273	167.871	153.94
Pass 3	196.349	180.044	192.77	176.789	192.03	176.104	189.1719	173.482
Pass 4	179.24	159.789	171.071	156.883	170.409	156.273	167.871	153.94
Pass 5	109.6	100.58	107.484	98.734	107.140	98.372	105.6714	96.907
Pass 6	0	0	0	0	0	0	0	0
Pass 7	0	0	0	0	0	0	0	0
Pass 8	0	0	0	0	0	0	0	0
Pass 9	0	0	0	0	0	0	0	0
Pass 10	157.13	139.513	149.343	134.976	148.786	134.443	146.37	134.1138
Pass 11	192.813	176.823	189.31	173.447	188.17	172.934	183.766	170.339
Pass 12	185.746	170.36	182.348	167.243	181.442	166.395	178.956	164.114
Pass 13	191.95	176.012	188.44	172.882	187.71	172.112	184.913	169.378
Cumulative	1573.46	1442.98	1544.872	1416.74	1538.883	1411.03	1410.293	1390.232
Area (sq m)	785398.1634	785398.16	785398.16	785398.16	785398.16	785398.16	785398.16	785398.16
Rate land use (kWh/sq m)	0.002	0.00184	0.00196	0.001794	0.00197	0.0018	0.00193	0.00177
Cost/kWh Per Year ($/kWh)	0.02177	0.02768	0.02414	0.0287	0.02433	0.0289	0.0231	0.0278

Analysis on the different rectenna size should be done since the costs of rectenna materials are increasing with the size of the rectenna. An optimum of rectenna size must be chosen to avoid the energy losses, which is cause by the electrical appliance is not being used by the consumers during the daytime. Refer to Table 2 for the result.

Table 2. The results for different radius with same latitude

	KUCHING	KUCHING	KUCHING	KUCHING	SKUDAI	SKUDAI	SKUDAI	SKUDAI
Latitude	1.0 degree	1.0 degree	1.0 degree	1.0 degree	1.1 degree	1.1 degree	1.1 degree	1.1 degree
Radius	400 meters	450 meters	500 meters	700 meters	400 meters	450 meters	500 meters	700 meters
	Power Max (kWh)	Power Max (kWh)	Power Max (kWh)	Power Max (kWh)	Power Max (kWh)	Power Max (kWh)	Power Max (kWh)	Power Max (kWh)
Pass 1	163.872	190.116	192.776	230.929	163.867	190.11	192.77	234.971
Pass 2	143.42	168.71	171.876	222.478	143.413	148.7049	171.871	221.467
Pass 3	163.872	190.116	192.776	230.929	163.867	190.11	192.77	234.971
Pass 4	143.42	168.71	171.876	222.478	143.413	148.7049	171.871	221.467
Pass 5	95.539	106.199	107.489	140.148	95.534	106.194	107.484	140.144
Pass 6	0	0	0	0	0	0	0	0
Pass 7	0	0	0	0	0	0	0	0
Pass 8	0	0	0	0	0	0	0	0
Pass 9	0	0	0	0	0	0	0	0
Pass 10	126.948	147.303	149.37	194.42	126.944	147.298	149.343	194.414
Pass 11	140.922	186.193	189.316	244.412	140.917	186.189	189.31	244.404
Pass 12	153.023	179.863	182.374	237.379	153.018	179.86	182.348	237.371
Pass 13	140.183	185.834	188.444	245.280	140.18	185.83	188.44	245.275
Cumulative	1313.226	1523.543	1544.872	2010.874	1313.182	1523.496	1538.885	2010.81

As cost is one of the industry major factors, it is essential to see the retina cost for each kWh. The retina's cost is depends on the size of energy demand and distance between the retina from the equator line.

Base on the result it shows that the suitable places for SPS 2000 Rectenna site in Malaysia are Skudai, Johor Bahru and Kuching, Sarawak since the cumulative power, 1538.885 kWh (rectenna at Skudai with 500m in radius), 1544.872 kWh which are almost the same with the theoretical value base on previous experiment which is about 1600 kWh. Basically, the project objectives had been successfully achieved.

V. CONCLUSIONS AND RECOMMENDATION

A. Concluding Remarks

An alternative energy is needed to replace the conventional energy sources to fulfill the energy demand Through this paper, concept of SPS 2000 has been studied and design of the computer program had been developed. Several issues involving the energy prediction had been tackled.

B. Limitation of The Computer Simulation

The developed computer program is limited to simulate the energy reception for countries that located at below 3 degree of latitude North or South only. The areas of rectenna surface considered are not over 2 km in diameter. Besides that, the inclination of the equator is only considered to be maximum and minimum condition during the year. The effects of earth inclination between these two conditions are not considered.

C. Suggestion for Future Works

Few studies have been made to fine better way the enhance the capability and usefulness of the research that was being studied. Few subsequent sub-chapters discussed the improvements that can be made to this research.

i. Satellite at GEO

In this project, the calculation is based on the positive of the satellite at LEO (Low Earth Orbit). This situation shortened the periods of power delivery. For further improvement the satellite should be put at GEO (Geo-stationary Earth Orbit) at about 35800 km from the Earth where it will lengthened the periods of power delivery. Raising the altitude can also increase the distance between North and South of the equator to which the satellite could deliver the power. For the time being, the rectenna is only suitable be sited in remote areas e.g Sarawak. In the future, when the SPS 2000 can be located at GEO, the rectenna can also be sited further up the northern Peninsular such as Kedah.

ii. Power Storage System

Since Malaysia in an equatorial country, it will receive a rainy season especially in June and December. This situation will affect the amount the received power during the rainy season. Thus, the considerations on the realistic power storage system cost are advice to be detailed.

iii. Land use plan

In some cases where the land beneath the rectenna is not a wasteland, there is a need for utilization of this land to be planned in parallel with plan for the rectenna and power distribution systems. This will maximize the land use especially for agricultural activities.

iv. Rectenna Efficiency

The study considered the overall rectenna efficiency at 80%. Present research and the development in rectenna technology is resulting in higher rectenna conversion and inverter inversion efficiency. This new development should be taken into consideration in future study on rectenna system.

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