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Commissioning and optimal load dispatch for supplying base and peak loads from Satellite Solar Power Station (SSPS) Using Microwave Wireless Power Transfer (MWPT)

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Abstract

Solar power on Earth is characterized by its intermittent nature, limiting its practical application to peak loads only. However, this limitation can be overcome by implementing a concept known as Satellite Solar Power Station (SSPS), which involves deploying solar panels in space. Nevertheless, this approach poses various challenges that need to be addressed. One of the primary obstacles lies in determining the feasibility of this plan. This research emphasizes the importance of exploring economically viable methods for establishing SSPS in space, utilizing a Reusable Launch Vehicle and Hohmann's Transfer technique. To support these proposals, optimization techniques involving multi-stage impulsive maneuvers are employed. Moreover, a comprehensive load dispatch algorithm is mathematically derived and developed to adapt to the changing demands on Earth, achieving a balance between load requirements and antenna size. In addition, discussions are conducted regarding the potential implementation of frequency reconfigurable Microwave systems for future applications. The overall objective of this study revolves around the future deployment and efficient load dispatch from SSPS to meet the energy demands of base loads on Earth, thereby making solar power a viable option.

Keywords Space Solar Power, Microwave Technology, Hohmann Transfer, Optimal Load Dispatch, Wireless Power Technology, Frequency Reconfigurable Systems

Introduction

Solar power on Earth is inherently intermittent due to factors, such as nightfall, cloud cover, and various environmental conditions. Consequently, it is not directly utilized for supplying the base loads required in terrestrial applications. However, when we shift our focus to space, the traditional concept of day and night loses its significance. Moreover, the absence of an atmosphere significantly reduces the occurrence of disruptive clouds. This presents an intriguing opportunity to transform solar power from an intermittent source to a continuous one, thereby making it feasible and practical for supporting base loads (Chaudhary & Kumar, 2018, Wang et al., 2021; Glaser et al., 1998). This realization prompts us to consider the installation of solar infrastructure in space to tap into the abundant solar energy available. To transmit this power to Earth, we can leverage the advancements in wireless power transfer technologies (Brown, 1984, 1992). Among these technologies, Microwave Wireless Power Transfer (MWPT) stands out as a promising solution. MWPT enables the capture of solar energy in space and its subsequent transmission to Earth using microwave technology. Over the past few decades, numerous proposals have emerged with the aim of achieving

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this goal (Wan and Huang, 2018). However, the feasibility and adaptability of such proposals have been questionable, making their implementation and practicality challenging.

Existing literature proposes the construction of solar infrastructure in various forms, such as Sun towers or clamshells (Glaser et al., 1998; Matsumoto and Hashimoto, 2007). The suggested approach involves initially deploying these structures in Low Earth Orbit (LEO) and subsequently transferring them to the geosynchronous orbit (Matsumoto and Hashimoto, 2007; Landis, 2012; NASA, 1978). To achieve this, proponents recommend employing Reusable Launch Vehicles for transportation to LEO, followed by the utilization of Orbit Dispatch vehicles to reach the geosynchronous orbit. Several missions conducted by NASA/DOE and JAXA have examined the potential power systems operating at frequencies of either 2.45 GHz or 5.8 GHz (Matsumoto and Hashimoto, 2007; Kim et al., 2016).

Solar power generated by the solar arrays in space is initially harnessed as direct current (DC) power, with efficiency ranging from 20% to 27.8%. Subsequently, this DC power is converted into microwaves for transmission to Earth, achieving an efficiency range of 70–75%. The transmission antenna then emits these microwaves with an estimated beam efficiency of 90%. Upon reaching Earth, the microwaves are received by rectennas, which convert them back into electrical power with an efficiency of approximately 80%. Throughout this entire process, it becomes apparent that the solar conversion stage at the outset of the process exhibits poor efficiency. However, if we can find ways to enhance the efficiency of this initial solar conversion, we have the potential to significantly improve the global power scenario (Chaudhary K & Kumar D, 2018).

From the beginning of the day until the end of the night, the electric load demand on Earth undergoes constant fluctuations (Wang et al., 2021). This dynamic nature of load demand has a direct impact on the frequency of microwaves required to meet this demand. Consequently, catering to peak loads becomes challenging due to the significant variation in frequency. Most microwave systems traditionally operate at a single fixed frequency, where the receiver and transmitter frequencies are precisely matched to maximize power transfer. However, recent advancements have introduced the concept of frequency reconfigurable systems, which offer the flexibility to adapt to variable load demands that influence the frequency profile (Kim et al., 2016; Dai et al., 2018; Zhong and Hui, 2018).

Based on the discussions conducted thus far, we can distill the essence of the scenario into a few key insights that establish Satellite Solar Power Stations (SSPS) as a viable and scalable solution for future sustainable energy objectives. First, the establishment of SSPS in space is paramount. Second, addressing the variable load demand on Earth is crucial to maintain adaptability. Finally, efficient solar power conversion through advanced solar panels plays a significant role. By successfully accomplishing these three aspects, a multitude of seamless opportunities would emerge, establishing SSPS as the highly sought-after solution. This research primarily concentrates on the assembly and load flow considerations for the future of SSPS.

The subsequent sections encompass an in-depth examination of the mathematical frameworks utilized for the positioning and optimization of SSPS assemblies in the methodology. The outcomes yielded by these mathematical frameworks are expounded upon and thoroughly discussed in the results and discussion section. In addition, this section comprises a flowchart that succinctly summarizes the entire progression of the paper. Ultimately, the paper culminates with a comprehensive conclusion and remarks pertaining to future prospects.

Methodology

In this section, we delve into a comprehensive discussion and derivation of the indispensable mathematical models that will prove instrumental in the commissioning of SSPS in space, encompassing crucial optimal conditions for dynamic load monitoring.

Installation and positioning of SSPS (commissioning)

Among the various literature available, discussions often revolve around the transfer of the SSPS setup, initially up to Low Earth Orbit (LEO) using a Reusable Launch Vehicle and subsequently up to geosynchronous orbit (GEO) through an orbit dispatch vehicle. However, these two-stage proposals involving expensive dispatchers can significantly impact the initial implementation costs. In the past, the cost factor has been a major contributor to the cancellation of several microwave proposals. In this research article, a proposal is presented, suggesting the use of a Reusable Launch Vehicle for transportation to LEO and then employing an Impulsive Maneuver based on Hohmann's transfer to ascend to the geosynchronous orbit. This proposal is supported by simulations to validate its feasibility. Hohmann's transfer technique played a pivotal role in the success of ISRO's Mangalyaan mission by significantly reducing costs. To illustrate this idea, mathematical modeling is an indispensable component. The suggested Hohmann's transfer requires the execution of impulsive maneuvers. To optimize fuel usage and minimize the required Δv (change in velocity), the transit from LEO to GEO is performed in multiple stages. The optimization process determines the intermediate stages to be included in the overall transit plan. The entire process commences with mathematical modeling of the scenario.

In this paper, the modeling of Hohmann's transfer assumes a simplified circular orbit as the starting point. The entire transit from Low Earth Orbit (LEO) to geosynchronous orbit (GEO) is divided into multiple fragments, with each fragment representing an intermediate stage. The Hohmann's transfer orbit between these two circular orbits is elliptical in nature. The specific iteration radii of the intermediate orbits are determined based on the chosen stages into which the overall transit is divided.

The vis-viva equation describes the relationship between the velocity, gravitational parameter, distance between orbiting bodies, and semi-major axis for an elliptical orbit. Mathematically, it is given by

$$v^2 = \mu\left(\frac{2}{r} - \frac{1}{a}\right) \quad (1)$$

where v: Velocity of the orbiting body; μ: Gravitational parameter; r: Distance between the orbiting bodies; a: Semi-major axis of the elliptical orbitWe can use this equation to calculate the velocity of an object in an elliptical orbit, given the values of μ, r, and a.

However, in the case of a circular orbit, we can modify the above equation using the following consideration:

$$r = a \quad (2)$$

In addition, the new equation for circular orbit becomes

$$v = \sqrt{\frac{\mu}{a}} \quad (3)$$

Now, let us take an equation that models change in velocity with dynamic mass change happening because of burn-outs:

$$\Delta v = -\int_{t_0}^{t_1} v_{\text{exh}}\left(\frac{\dot{m}}{m}\right)dt \quad (4)$$

where Δv: Change in velocity; v_{exh}: Exhaust velocity of the spacecraft; $\dot{m}$: Mass flow rate of the spacecraft; m: Mass of the spacecraft; t_0, t_1: Initial and final times of the propulsion event.

Changing the integration variable from t to m gives

$$\Delta v = -\int_{m_0}^{m_1} v_{\text{exh}}\frac{dm}{m} \quad (5)$$

where m_0, m_1: Initial and final masses of the spacecraft. The final equation after solving the above equation is

$$\Delta v = v_{\text{exh}} \ln\left(\frac{m_0}{m_1}\right) \quad (6)$$

The above equation is referred to as 'Tsiolkovsky's Rocket Equation'. Making use of Eq. (3), we can calculate the Δv and hence using Eq. (6) we can calculate the propellant mass ratio of each stage to plan the whole mission in terms of feasibility. The propellant mass ratio stands out to be a good indicator of fuel consumption during multi-stage burnouts.

In this research paper, two multi-stage optimization approaches were employed to calculate the Δv (change in velocity) required for the mission. One approach consisted of six stages, while the other involved ten stages. The propellant chosen for this case study is hydrazine, which offers an exhaust velocity range of 2100–2560 m/s. Hydrazine has gained popularity as a propellant for both attitude control systems (ACS) and main propulsion systems of satellites. It provides reliable and efficient propulsion for various satellite operations, including orbit insertion, orbit adjustments, station-keeping, and attitude control. Hydrazine possesses several advantages as a rocket propellant. It exhibits a high specific impulse, enabling efficient utilization of propellant mass. In addition, hydrazine is highly hypergolic, meaning that it spontaneously ignites upon contact with an oxidizer, such as nitrogen tetroxide (N2O4). This property ensures reliable ignition without the need for an ignition system. The mass of the entire rocket system considered in the case study is approximately 15,000 kg. It is important to note that this mass value is intended for illustrative purposes based on the study, and actual system designs and calibrations may lead to different figures.

The future of installation does not have to restrict itself merely to geosynchronous orbits. We can use much better parking spots for commissioning our SSPS in space. One of the better choices can be Lagrange Points. One can easily carry out the analysis for the Sun–Earth system using circular restricted three-body problems. It takes into account the gravitational forces and the centrifugal force acting on a smaller object in the presence of two larger celestial bodies. The potential energy equation used to form the potential energy contours is

$$U(x,y) = -\left(\frac{\mu_1}{r_1}\right) - \left(\frac{\mu_2}{r_2}\right) - \frac{1}{2}\omega^2(x^2 + y^2) \quad (7)$$

where U(x, y): Potential energy at coordinates; μ_1: Mass ratio of the primary body; μ_2: Mass ratio of the secondary body; r_1: Distance between the coordinate and the primary body; r_2: Distance between the coordinate and the secondary body; ω: Angular velocity of the system; x, y: Cartesian coordinates.

A range of coordinates surrounding each Lagrange point is utilized to plot the potential energy contours. A grid of potential energy values is created by computing the potential energy at each position using the equation above. These numbers are then used to generate a contour plot, which depicts lines of constant potential energy on a two-dimensional graph. Lagrange points form the saddle points in the contour graph with zero potential energies. This point gives you stable parking points for the installation of SSPS.

Optimally fulfilling the load demand on Earth

The electric load on Earth is characterized by its dynamic and non-constant nature. These fluctuations in the load directly impact the frequency requirements of Microwave Wireless Power Transfer (MWPT) systems. Traditionally, most MWPT systems operate at fixed frequencies. However, recent advancements have introduced frequency reconfigurable systems that can adapt and change frequencies as needed. The ability to reconfigure frequencies is a crucial feature for the future of SSPS in meeting both base and peak load demands.

Implementing frequency reconfigurability involves making adjustments to the antenna design specifications, which can be achieved through intelligently monitored self-evolving structures. This approach allows for changes in antenna size corresponding to the varying frequency requirements. However, this process is governed by two key constraints. First, it is important to maintain proper beam efficiency to ensure efficient power transmission. Second, the design should not violate the near-field region constraint, ensuring that the system operates within the desired range.

Many antenna designs have been developed to satisfy these conditions, resulting in a reduction in antenna size as the frequency increases, particularly when there is an increase in load demand. This trend is often observed in cases where the minimum near-field condition or Fresnel zone is not compromised.

The implementation of SSPS does not involve a single satellite; instead, it consists of a cluster of satellites that collectively host the solar array. Let us consider 'n' satellites in the SSPS configuration, which are designed to meet specific load demands on Earth. The ultimate objective is to minimize the antenna size while ensuring adherence to the near-field constraint to satisfy the power demand.

To address this challenge, the problem was tackled using the Kuhn–Tucker Method, incorporating the use of Lagrange Multipliers. This optimization technique allowed for the optimization of the antenna size, taking into account the constraints imposed by the near-field region. By applying the Kuhn–Tucker Method and incorporating Lagrange Multipliers, an optimal solution was derived to minimize the antenna size while meeting the specified power demand requirements for the SSPS configuration.

Let, P_d: Total load demand; A_t: Total transmission antenna area; P_g: Total generation from all satellites in SSPS.

Total transmitting antenna area is

$$A_t = A_1 + A_2 + A_3 + \ldots + A_n \tag{8}$$

where

$$A_t : \text{Total transmission antenna area}$$
$$A_1, A_2, A_3, \ldots, A_n : \text{Individual areas of transmission antennas}$$

This can be summarized as

$$A_t = \sum_{i=1}^{n} A_i \tag{9}$$

where:

$$A_t : \text{Total transmission antenna area}$$
$$A_i : \text{Individual areas of transmission antennas, where } i = 1, 2, \ldots, n$$

The generated power should balance the load demand for optimal supply. This equation is called as 'equality constraint'.

$$\sum_{i=1}^{n} P_{g_i} = P_d \tag{10}$$

where

$$P_{g_i} : \text{Generation from single unit} i$$
$$P_d : \text{Total Load demand}$$

Modifying the equation. we get

$$P_d - \sum_{i=1}^{n} P_{g_i} = 0 \tag{11}$$

Writing minimization equation for the area using the Lagrange Multiplier concept, we get

$$A = A_t + \lambda \cdot f \tag{12}$$

where A: Total area; A_t: Total transmission antenna area; λ: Lagrange multiplier; f: Equality constraint.

For getting the minima (solution to the antenna area minimization problem for optimal load dispatch) we need to substitute the value from (11) in (12) and then evaluate

$$\frac{\partial A}{\partial P_{g_i}} = 0 \tag{13}$$

Upon doing, we get

$$\frac{dA_i}{dP_{g_i}} = \lambda \tag{14}$$

The equation mentioned above represents the condition that enables the minimization of the transmission antenna area while meeting the load demands on Earth. This equation plays a crucial role in ensuring proper synchronization and coordination among the satellite cluster within the SSPS system. By satisfying this condition, the subsystems of SSPS can be effectively synchronized, allowing for the development of algorithms that optimize the fulfillment of load demands on Earth. These algorithms utilize the equation to determine the optimal configuration and operation of the satellite cluster, thereby maximizing the efficiency and effectiveness of power delivery to meet the load demands.

For transmission antenna: The Friis equation (Friis, 1946) relates the Power of the transmission antenna to the Antenna Size (area) using the relation below:

$$P_t = \frac{P_d \cdot \lambda^2 \cdot D^2}{A_t} \tag{15}$$

where P_t: Transmission Antenna Power; P_d: Total load demand Power; λ: Wavelength; D: Specified distance over which the power is delivered; A_t: Total transmission antenna area.

Rearranging we get

$$A_t = \frac{P_d \cdot \lambda^2 \cdot D^2}{P_t} \tag{16}$$

Now, to get the minimization for the area under power constraint, we need to differentiate Eq. (16) as per the derived norm in Eq. (14). By doing so, we get the value of the optimal minimization factor (lambda):

$$\frac{dA_t}{dP_t} = -\frac{P_d \cdot \lambda^2 \cdot D^2}{P_t^2} \tag{17}$$

From the above equation, we need to keep this $\frac{dA_t}{dP_t}$ constant for all satellites in SSPS to minimize the total antenna area at high frequency to supply the demanded power.

For solar panel: A similar sort of analysis can be extended and used to find the optimal working points, wherein satellites can generate the demanded solar power in the minimum possible area using proper solar inclination angles. For this, start with the following modeling

$$P = A \cdot G \cdot \eta \tag{18}$$

where P: Power output; A: Area; G: Irradiance or Solar radiation; η: Efficiency.

If θ is the angle between normal to the solar panel and the direction of solar irradiance, then

$$P = A \cdot \cos(\theta) \cdot G \cdot \eta \tag{19}$$

where

θ : Angle of incidence

Differentiating the above equation gives

$$\frac{dA}{dP} = \frac{1}{\cos(\theta) \cdot \eta \cdot G} \tag{20}$$

We need to satisfy the above condition for all solar panels to make sure that the minimum area from the whole cluster is utilized for meeting the load demands.

Results and discussion

Within this section, we employ software tools to validate the mathematical models utilized for our research endeavors. A representative case is selected to extend the optimization process for commissioning. Consequently, plots illustrating the optimal load dispatch for both the antenna and solar panel are generated based on the derived conditions

Hohmann-based maneuver optimization for reducing the Δ*v* values

Section "Installation and positioning of SSPS (commissioning)" describes the essential assumptions and parameters for carrying out Hohmann-based optimization. Considering 15,000 kg payload (satellite and propellant mass) as initial mass with an exhaust velocity of 2500 m/s transiting from LEO to geosynchronous orbit gives results for six stages and ten stages maneuver captured in Table 1.

It can be easily inferred from the table that Δv values for six stages maneuver is more than the ten stage maneuver. The propellant ratio here is defined as the ratio of the initial mass to the final mass. If the final mass reduces at a higher rate (more fuel being burned), then the propellant ratio will be a big number, because the ratio is inversely proportional to the final mass. For many stages, the propellant ratio for ten stages is less than six stages meaning that the final mass of ten stage maneuver was high because of less fuel being burnt. This illustrates that multi-stage Hohmann transfer can stand out as a better and more economical way of transitioning from LEO to the geosynchronous orbit.

Table 1 Optimization results

Stage	6 stages maneuver		10 stages maneuver	
	Δv (in m/s)	**Propellant Ratio**	**Δv (in m/s)**	**Propellant Ratio**
Stage 1 (start)	0	1.0000e+00	0	1.0000e+00
Stage 2	1.3360e+04	2.0938e+02	1.1538e+04	1.0100e+02
Stage 3	1.5420e+04	4.7731e+02	1.3951e+04	2.6514e+02
Stage 4	1.6397e+04	7.0539e+02	1.5140e+04	4.2659e+02
Stage 5	1.6995e+04	8.9599e+02	1.5880e+04	5.7356e+02
Stage 6	1.7609e+04	1.0574e+03	1.6397e+04	7.0539e+02
Stage 7	–	–	1.6785e+04	8.2370e+02
Stage 8	–	–	1.7089e+04	9.3037e+02
Stage 9	–	–	1.7336e+04	1.0271e+03
Stage 10	–	–	1.7542e+04	1.0357e+03

Potential energy contour for finding Lagrangian parking points in Sun–Earth Orbit

In "Installation and positioning of SSPS (commissioning)" section, this paper describes the plotting of potential energy contours, with distances represented in Astronomical Units (A.U.). The figure presented in the section showcases these contours, with the Lagrange points marked as red dots. Notably, the contour plot reveals saddle points, where the potential energy is zero. This analysis serves as an example and highlights the possibility of utilizing three-body problems to identify suitable parking points for establishing the SSPS. It is important to note that this section serves as an illustrative demonstration, offering a glimpse into the potential future applications of SSPS. (Please refer to the figure, where the yellow dot represents the Sun and the blue dot represents the Earth) (see Fig. 1).

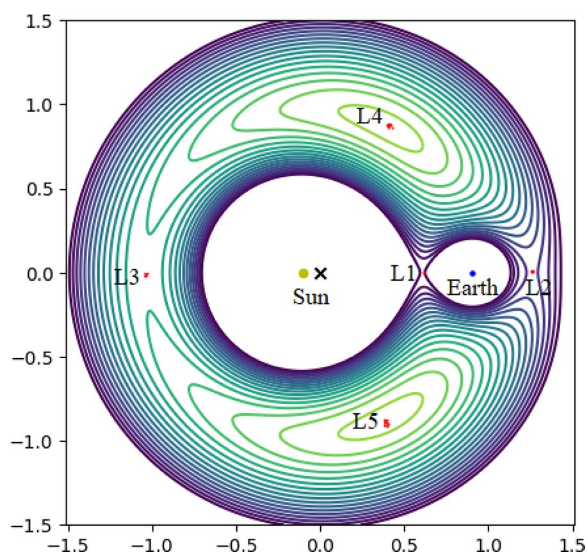


Fig. 1 Lagrange points in the Sun–Earth Orbit

Optimization of transmission antenna size and effective area of the panel for generation

For Transmission Antenna: From equation (17) we get,

$$\frac{dA_t}{dP_t} = -\frac{P_d \cdot \lambda^2 \cdot D^2}{P_t^2} \tag{21}$$

For n satellites, we can write

$$-\frac{P_d \cdot \lambda^2 \cdot D_1^2}{P_{t1}^2} = -\frac{P_d \cdot \lambda^2 \cdot D_2^2}{P_{t2}^2} = \ldots = -\frac{P_d \cdot \lambda^2 \cdot D_n^2}{P_{tn}^2}$$

In the case of a cluster of satellites in an SSPS, the power demand to be fulfilled at a specific time is generally uniform for all satellites. The value of lambda, representing a parameter associated with the operating frequency, remains constant for all satellites in the cluster. The distinguishing factors among the satellites in the SSPS cluster are their designated distances (D) from the Earth's load center and their respective power generation shares (Pt). Thus, the simplified representation for n satellites in the SSPS cluster can be expressed as follows:

$$\frac{D_1^2}{P_{t1}^2} = \frac{D_2^2}{P_{t2}^2} = \ldots = \frac{D_n^2}{P_{tn}^2}$$

To ensure optimal load dispatch in the SSPS, it is crucial for the ratio mentioned above to remain constant across all satellites. By utilizing the distance (D) and power generation share (Pt) values from a satellite with good antenna directivity, the ratio can be calculated. Subsequently, these calculated values can be implemented by all satellites in the SSPS, enabling them to fulfill the load demand while minimizing the transmission antenna area.

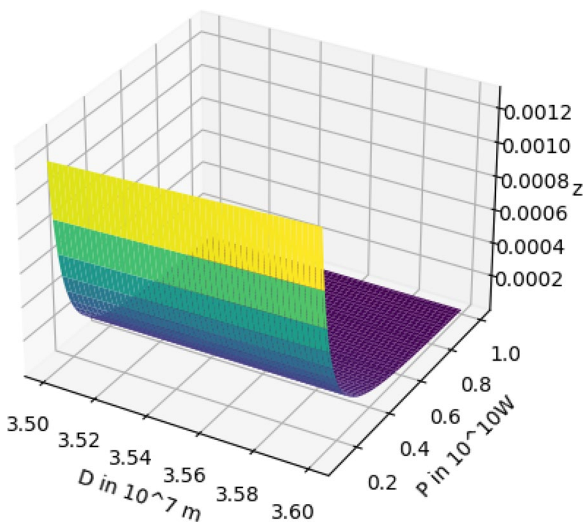


Fig. 2 Value of $\frac{D^2}{P^2}$ for different combinations at different Lines of Sights in geosynchronous orbit

A plot depicting the variation of the ratio for different distance values within the geosynchronous orbit range, with a line of sight ranging from 35,000 km to 36,000 km and power varying from 1 GW to 10 GW, is providedin Fig. 2. These plots serve as valuable references to determine the appropriate lambda value and adjust the distance (D) and power generation share (Pt) for all satellites in the Satellite Solar Power Stations, facilitating efficient load dispatch.

For Solar Panel: From equation (20) we get,

$$\frac{dA}{dP} = \frac{1}{\cos(\theta) \cdot \eta \cdot G} \tag{22}$$

For n solar panels in the Satellite Solar Power Stations cluster, we can write

$$\frac{1}{\cos(\theta_1) \cdot \eta_1 \cdot G} = \frac{1}{\cos(\theta_2) \cdot \eta_2 \cdot G} = \ldots = \frac{1}{\cos(\theta_n) \cdot \eta_n \cdot G}$$

The incidence angle of solar panel arrays can vary at different times, allowing for optimization of their efficiency. While the efficiency of solar panels may appear fixed, it can be adjusted by modifying the thermal conditions. This can be accomplished by incorporating focusing lenses over the solar panels, resulting in a significant increase in efficiency by several percentages. The irradiance function (G) remains constant across various points in the geosynchronous orbit. Hence, the simplified model for solar panels in the Satellite Solar Power Stations can be represented as follows:

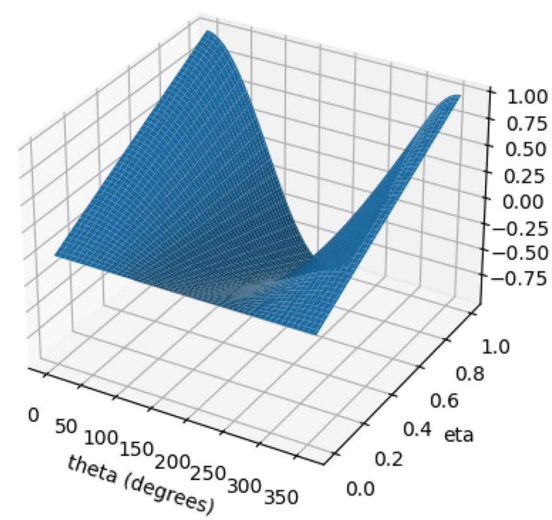
$$\frac{1}{\cos(\theta_1) \cdot \eta_1} = \frac{1}{\cos(\theta_2) \cdot \eta_2} = \ldots = \frac{1}{\cos(\theta_n) \cdot \eta_n}$$

or

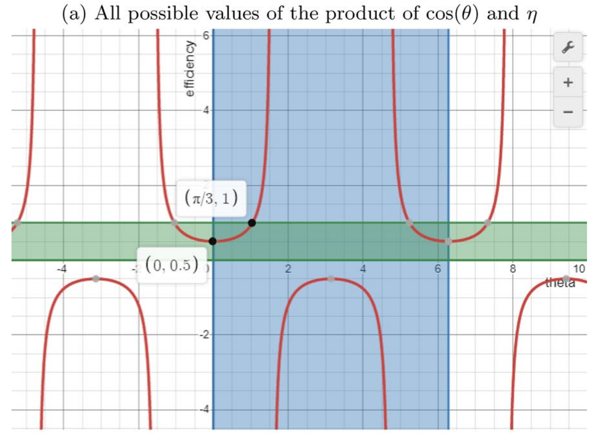
$$\cos(\theta_1) \cdot \eta_1 = \cos(\theta_2) \cdot \eta_2 = \ldots = \cos(\theta_n) \cdot \eta_n$$

The ratio described above must remain constant for the solar panels on all satellites within the Satellite Solar Power Stations cluster. To achieve this, the optimum value of the product $\cos(\theta) \cdot \eta$ should be chosen from the satellite with the maximum directivity towards the Earth's load region. The product $\cos(\theta) \cdot \eta$ for other satellites can be adjusted to match this value by modifying the inclination angles and lens concentration to thermally vary the cell efficiencies.

The range of $\cos(\theta)$ is between − 1 and 1, while the efficiency η typically varies between 0 and 1. As a result, the product $\cos(\theta) \cdot \eta$ can range from − 1 to 1. Figure 3a illustrates the variation of the product $\cos(\theta) \cdot \eta$ for different



(a) All possible values of the product of $\cos(\theta)$ and η



(b) Values of θ and η that give a constant value (=0.5)

Fig. 3 Optimization for Solar Panel Area values, while Fig. 3b represents all possible combinations of $\cos(\theta)$ and η that yield a fixed product. This information is particularly useful when the satellite with maximum directivity has determined the desired product of $\cos(\theta) \cdot \eta$, and other satellites need to adjust their $\cos(\theta)$ and η values to satisfy this condition.

In the provided example, a fixed value of 0.5 is considered, and Fig. 3b shows all possible combinations of θ and η that result in a product of 0.5. The red curve in the intersecting region between the blue zone (angles ranging from 0 to 360 degrees) and the green zone (efficiency ranging from 0 to 1), indicates the viable solutions that meet the necessary conditions.

Optimization load dispatch algorithm for supplying load demand with minimum antenna area

To achieve optimal load dispatch in the Satellite Solar Power Stations system, it is crucial to accurately calculate and estimate the working frequency based on the load demand on Earth. This frequency will serve as a key parameter for determining the near-field region and, consequently, for calculating the minimum area required for the transmission antenna. As per the optimal condition derived in previous sections, the value of lambda needs to be set. A prudent approach is to select lambda using the D and P parameters of the satellite with the highest directivity towards the Earth's load zone. Subsequently, the D and P values of the other satellites can be adjusted to match this lambda value, facilitating optimal load dispatch.

However, before implementing these values, it is necessary to utilize the optimal D and P values calculated earlier to estimate the area using the Friis equation. The sum of the total antenna areas of all satellites should exceed the area limit specified by the near-field conditions. If the sum is greater, the optimal values can be implemented. If not, the D and P values should be readjusted, and the procedures should be repeated. Once the proper values of D and P are implemented for optimal load dispatch, the same set of procedures can be repeated periodically because the load demand is dynamic and continuously changes over time. All of these is inferred in form of flowchart given below (Fig. 4)

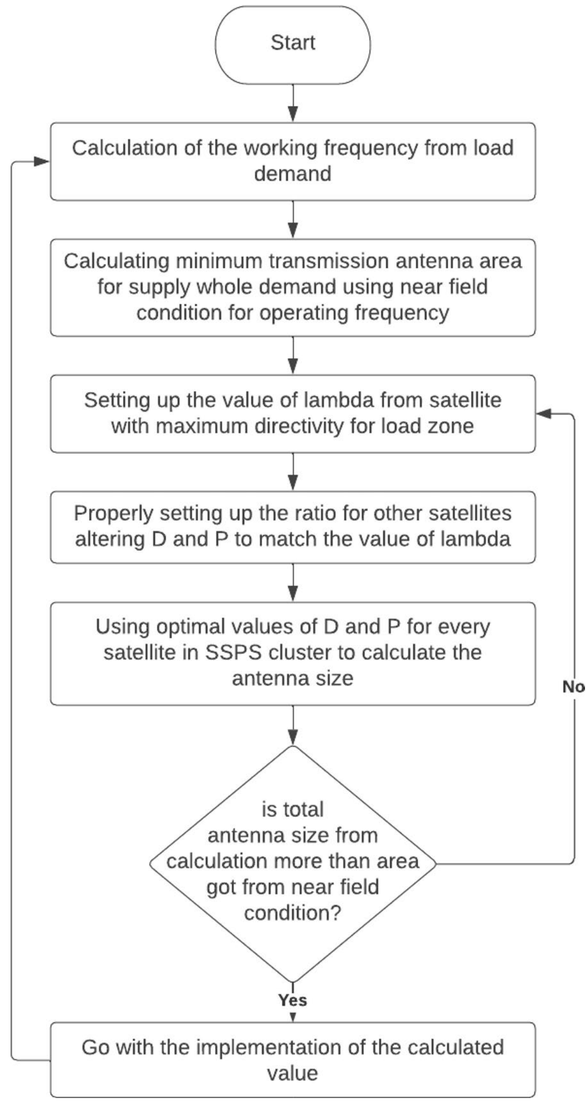


Fig. 4 Algorithm for the implementation of the otimal load dispatch

Conclusion

This research work explores the potential of Satellite Solar Power Stations (SSPS) as a base load solution and discusses various strategies to make SSPS feasible and effective in the future. The study highlights the advantages of using multi-stage Hohmann Transfer for clustering SSPS satellites in geosynchronous orbit. It emphasizes that increasing the number of stages in the transfer can reduce impulsive velocity and fuel consumption, making it a favorable option.

The importance of frequency reconfigurability in Microwave Wireless Power Transfer (MWPT) systems is emphasized, and the research presents a mathematical optimization theorem that minimizes the antenna area required for efficient load dispatch to meet Earth's power demands. A similar analysis is conducted for optimizing solar panel areas, aiming to enhance the overall efficiency and economy of the SSPS system.

The proposed Orbit Load Dispatch algorithms offer promising approaches for optimizing SSPS operations, making it a highly sought-after base load system with significant capabilities. The future prospects of this research open up numerous opportunities for meeting load demands through SSPS, contributing to the realization of a sustainable and net-zero energy future.

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Author contributions
Prasad Rathod played a pivotal role in the study, taking charge of the overall design, derivation of all mathematical relations, meticulous data analysis, and comprehensive manuscript preparation. Their expertise and intellectual contributions significantly shaped the research direction and ensured the accuracy and robustness of the findings. Abdullah Al Mahamud made substantial contributions by designing and implementing intricate simulation codes, which were instrumental in exploring various aspects of the study. Their valuable guidance throughout the research process enhanced the quality and reliability of the results. Additionally, Utkarsh Talele provided valuable assistance by sharing additional codes, offering insightful guidance, and actively participating in the revision process of the manuscript. Collectively, the authors collaborated closely, drawing upon their respective expertise, to achieve a cohesive and high-quality research outcome. All authors critically reviewed and approved the final version of the manuscript, demonstrating their commitment to scholarly excellence.

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This study does not involve the use of specific data or materials. Therefore, there are no data or materials available for sharing.

Declarations

Ethics approval and consent to participate
This study does not involve human participants. Therefore, ethics approval and consent to participate are not applicable.

Consent for publication
As this study does not include any identifying information of participants, consent for publication is not applicable.

Competing interests
The authors declare no competing interests in relation to this research. There are no financial or personal relationships that could potentially bias the interpretation or presentation of the research findings.

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