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ORBITING SOLAR REFLECTORS: A PATHWAY TO EXTENDED SPACE-BASED SOLAR POWER AVAILABILITY AND ENHANCED GRID STABILITY

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Abstract

The transition to clean energy resources such as solar energy is critical for the battle against climate change and to achieve net zero emission goals. However, one of the challenges solar energy faces is its dependence on daylight hours only for energy production. This challenge restricts the availability of solar energy after daylight hours which leads to reliance on fossil fuel generators during peak demand periods, thus, increasing CO2 emissions. To overcome this challenge, orbiting solar reflectors (OSRs) were proposed as a future technology which can reflect sunlight to terrestrial solar power farms (SPF) from space during dawn and dusk. This paper aims to explore the integration of OSRs into SPFs to extend the availability of energy after hours of sunlight and reduce carbon emissions by reducing dependency on fossil fuel generators. Furthermore, the paper discusses how OSRs can contribute to the stability of the voltage of the power grid. The results show that the OSR could significantly boost the energy output of a SPF during these periods, thereby extending the availability of solar energy and decreasing the reliance on fossil fuel generators. This technology has the potential to reduce carbon emissions, which contributes to global efforts to reduce climate change. Furthermore, the findings illustrate how OSRs can help maintain voltage stability in the power grid by providing more energy during the peak demand period.

1 Introduction

The quest for reliable and sustainable energy sources has never been more urgent as the world grapples with the dual challenges of meeting increasing energy demands and reducing greenhouse gas emissions [1]. Solar energy, one of the most promising renewable energy sources, is currently limited by its dependence on daylight hours. This inherent limitation restricts the availability of solar energy to times when the sun is above the horizon, necessitating the use of fossil fuel generators to bridge the gap during periods of peak demand, especially during dawn and dusk. Addressing this limitation is crucial to improving the role of solar power in our energy systems and reducing our dependence on non-renewable sources [2].

In response to these limitations, the concept of harnessing solar energy beyond the Earth's atmosphere has gained traction. Space-based solar power (SBSP) involves collecting solar energy in space, where sunlight is more abundant and uninterrupted by atmospheric conditions and transmitting it to Earth [3]. The concept of SBSP was first introduced in the science fiction writings of Isaac Asimov in 1941. However, it was later developed into a scientific research field for implementation by Peter Glaser in 1968 [4]. Early research focused on the feasibility of collecting solar energy in space and transmitting it to Earth using microwave or laser transmission. However, the cost and complexity of implementing and maintaining such systems have been major hurdles [5][6].

Among the innovative solutions proposed within the SBSP paradigm are OSRs. These are large reflective structures placed in orbit around the Earth, designed to redirect sunlight to specific areas on the planet's surface [7]. By optimally positioning these reflectors, it is possible to extend the availability of sunlight to SPFs during dawn and dusk, traditional periods of lower solar energy production [8]. This redirection of sunlight can significantly boost the energy output of SPF during these critical hours, improving the overall stability and reliability of the power grid, reducing the need for fossil fuel-based peak power plants, and improving the integration of renewable energy into the grid.

This paper aims to explore the potential of OSRs to extend the availability of solar energy beyond daylight hours and improve the stability of the power grid. By focussing on the impact of these reflectors on the energy output of SPFs during dawn and dusk, this work seeks to demonstrate how OSRs can reduce reliance on fossil fuel generators, decrease CO_2 emissions, and contribute to global efforts to combat climate change. The rest of the paper organized as follows: Section 2 presents the main concept of OSRs and the methodology used is defined in Section 3. Results are discussed in Section 4 and the work is concluded in Section 5.

2. The Orbiting Solar Reflectors

OSRs represent a forward-thinking approach to enhancing the effectiveness of solar energy collection in space and sending it to Earth. The reflectors can be as large as several kilometres in diameter. They consist of lightweight membrane structures

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designed to orbit the Earth and reflect additional sunlight onto terrestrial SPF. This reflected sunlight increases the efficiency and output of the SPF, particularly during periods when natural sunlight is weak, such as at dawn and dusk, or when sunlight is completely absent [9].

2.1 Principle of Operation

The concept behind OSRs is to maximize the availability of sunlight to solar panels on the ground. Reflectors are positioned in space in such a way that they can catch sunlight and redirect it to a SPF on Earth. They are placed in an optimal position on a low orbit close to the terminator area, which is the boundary where day transitions to night. By arranging the reflectors in a constellation, these reflectors can extend the duration of effective sunlight exposure for solar panels beyond the natural daylight hours in a scalable and predictable way. This setup involves multiple reflectors being placed in a precise pattern around the Earth to ensure continuous and consistent coverage, as shown in Fig. 1. The use of algorithms helps to determine the optimal orbital position and orientation of the reflectors to maximize the amount of sunlight reflected to the SPF at early morning and late evening [8].

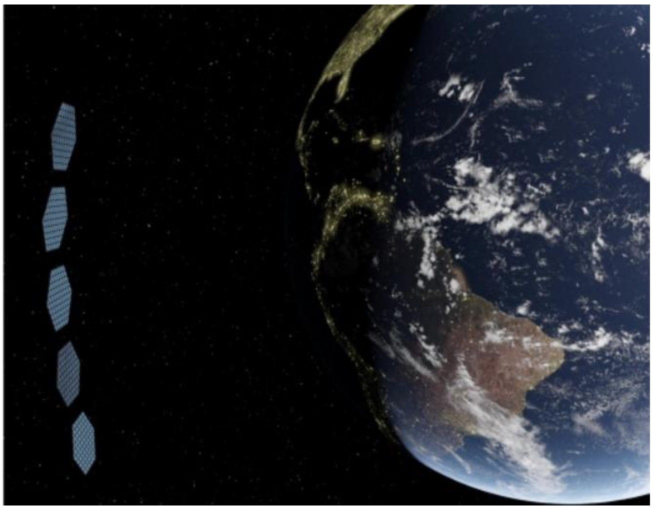

Fig. 1 Initial visualization of a reflectors in Earth orbit. Credits: Andrea Viale, NASA (Earth texture)

2.2 Structure and Composition

The main structure of the OSRs is designed to be as lightweight and durable as possible to facilitate their deployment and stability in orbit. Typically, these reflectors are described as "gossamer-thin," highlighting their delicate and lightweight nature. The materials used for these reflectors are highly reflective, such as aluminium foil, which can efficiently redirect sunlight without adding significant weight [7]. This design was first demonstrated in early 1993 when a 20-metre aluminium foil Znamya reflector was released from the Russian Mir space station to reflect sunlight back to Earth, shown in Fig. 2 [10].

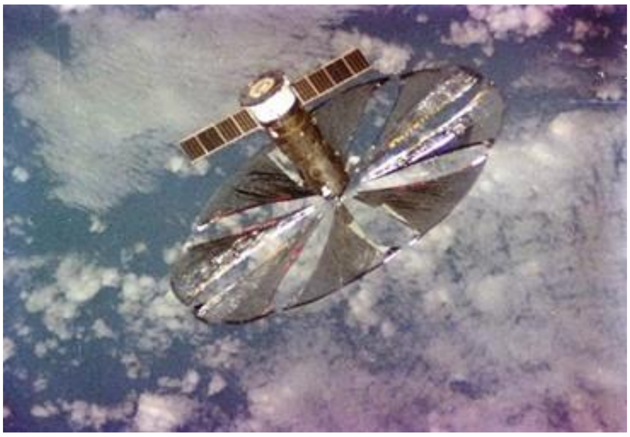

Fig. 2 Russian space mirror experiment Znamya-2. Credits: Wikipedia, RSC Energia CC-BY-4.0

Recently, these reflectors were designed to be up to kilometre-wide to provide a reflected area 10 km across on the Earth's surface and provide more significant enhancements to SPF output. It was shown that possible to generate substantial additional electricity by positioning multiple reflectors in the low Earth orbit. For instance, a setup involving 20 reflectors in a 1,000-kilometer orbit could potentially provide an extra 728 megawatt-hours of electricity per day, equivalent to the output of an additional large-scale SPF without the need for constructing new infrastructure on the ground [8][11].

2.3 Research and Development

The development of OSR technology is part of broader research initiatives aimed at addressing global energy needs and combating climate change. Projects such as SOLSPACE, led by the University of Glasgow and supported by the European Research Council, are at the forefront of this research. These initiatives explore the technical and economic feasibility of deploying such reflectors on a large scale [12]. The SOLSPACE project is focused on the design, development, and laboratory-scale demonstration of these technologies to provide global clean energy services [13]. The falling costs of launching payloads into space and advances in reflector technologies and deployment techniques are making the concept of OSRs increasingly viable. As these technologies mature, they have the potential to significantly improve the efficiency of solar energy systems around the world, thus playing a crucial role in the transition to sustainable energy sources and the reduction of reliance on fossil fuels [14].

3. Methodology

To evaluate the impact of OSRs on SPF output and grid stability, several steps are involved. The first step is to understand the working functionality of OSRs, which are designed to redirect sunlight to solar panels. Subsequently, an analysis of network power flow was conducted to examine how the additional energy generated by OSRs is distributed within the power grid. This involves studying the dynamics of the daily flow of energy and the integration of additional power into the existing grid as shown in Fig. 3, ensuring an efficient and stable distribution of electricity.

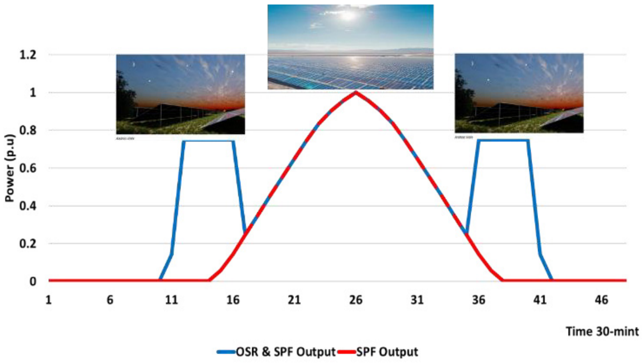

Fig. 3 Daily SPF power output illustration (image credit: Andrea Viale and stockcake.com)

3.1 Case Study

For model validation, the IEEE 9 bus system is used as a case study. The system is used in this paper, to highlight the effects of OSRs on the electrical grid and the SPF. The system has 9 buses, 3 generators, 3 transformers and 6 transmission lines. It consists of 3 general loads which total up to 315 MW and 115 MVar. The technical data sheet can be found in [15]. The SPF is connected in Bus 5 with 240MW optimal size of the is [16]. The case study modelling and the power flow calculation were conducted in MATLAB. The single line diagram of the IEEE 9 bus system with the SPF and the OSR is shown in Fig. 4 [17].

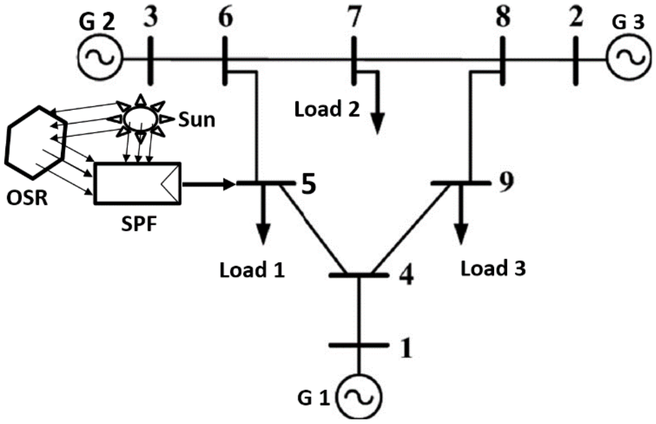

Fig. 4 Single line diagram of IEEE 9 bus system with SPF and OSR

3.2 Assumptions

For clarity and consistency, the assumptions made in this study are outlined as follows:

- Orbit geometry consideration: Due to the orbit geometry of the problem the OSR spot size will be larger than the physical size of the 240 MW SPF. However, for purposes of illustration for this initial analysis, it will be assumed that up to all the OSR energy can in principle be collected by the SPF. Future analysis will be required for large SPF which are of a similar physical size to the OSR spot size. Here, the OSR input to the SPF in MW is assumed to be 25%, 50%, 75% and 100% of the SPF size MW.
- SPF configuration: A SPF with a capacity of 240 MW is connected to Bus 5 within the IEEE 9-bus system [16].
- Reflector duration: Reflectors are assumed to redirect sunlight towards the SPF for a total of 5 hours daily, specifically 2.5 hours at dawn and 2.5 hours at dusk periods, to enhance solar energy capture during low sunlight hours [11][18].
- Source of data: The load profile data is derived from a previous study conducted by [19], while the SPF profile is obtained from the Renewables Ninja website [20].
- Profiles: The OSR profiles are adjusted to correspond to 25%, 50%, 75%, and 100% of the SPF capacity, representing different levels of solar resource optimization. Both the load and SPF profiles are normalized to the maximum and remain consistent across all scenarios to maintain a uniform basis for comparison. All profiles are based on 24-hour data, recorded at 30-minute intervals, providing a detailed temporal analysis of system performance.
- Weather conditions: It is assumed that the weather conditions are characterized by a clear sky throughout the study period, ensuring maximum solar irradiance.
- Transmission Line Loses: Transmission line loses are not considered in this study, focusing solely on the generation and consumption aspects of the system.

In the power flow analysis phase, the energy output in megawatt hours (MWh) was calculated by summing the area under the power curve for various scenarios. These scenarios include power generation solely from conventional generators, from generators combined with a SPF, and from generators supplemented by SPFs with OSRs. Finally, a comprehensive power system analysis was performed focusing on energy MWh and voltage stability. This analysis evaluates how the integration of OSRs influences the overall stability of the power system, ensuring that the voltage levels remain within acceptable limits and the grid operates reliably under different conditions. The effectiveness of OSRs in enhancing SPF generation and maintaining grid stability was thoroughly assessed through comparing the different scenarios.

3.3 AC Power Flow and Voltage Analysis

Alternating current (AC) power flow analysis is fundamental in electrical engineering to understand how electric power is transmitted and distributed across a power grid. It involves calculating the voltages, currents, real power (P), and reactive power (Q) throughout the network under steady-state conditions. The key equations that govern AC power flow are based on Kirchhoff's laws and the complex power formula [21]. In this study, the power flow equations are non-linear and were solved using the Newton-Raphson iterative numerical method. This method adjusts the voltages and phase angles iteratively until the power balance equations are satisfied across the network. The power flow in an AC system can be described using the following equations. The complex power formula can be represented as follows [22].

$$S = P + jQ \tag{1}$$

where S is the complex power, P is the real power, Q is the reactive power and j is the imaginary unit. For power flow in terms of voltages and admittances for a bus i in a power system, the injected complex power S_i can be expressed as:

$$S_i = V_i I_i^* \tag{2}$$

where V_i is the voltage at bus i and I_i^* is the complex conjugate of the current injected into bus i. Electrical current I_i in terms of admittance matrix on bus i can be written as:

$$I_i = \sum_{j=1}^{n} Y_{ij} V_j \tag{3}$$

where Y_{ij} is the element of the bus admittance matrix (Y-bus) corresponding to buses i and j, V_j is the voltage at bus j and n is the total number of buses. Combining these equations and substituting the current equation into the power equation gives:

$$S_i = V_i \left(\sum_{j=1}^{n} Y_{ij} V_j\right)^* \tag{4}$$

Separating this into real and reactive components, we obtain:

$$\begin{aligned} P_i &= V_i \sum_{j=1}^{n} \left|V_j\right|\left(G_{ij}\cos\,\theta_{ij} + B_{ij}\sin\,\theta_{ij}\right) \\ Q_i &= V_i \sum_{j=1}^{n} \left|V_j\right|\left(G_{ij}\sin\,\theta_{ij} - B_{ij}\cos\,\theta_{ij}\right) \end{aligned} \tag{5}$$

where G_{ij} are the real and imaginary parts of the element of the admittance matrix Y_{ij} and θ_{ij} is the phase angle between buses i and j. P is the actual power generate by the generators or consumed by the loads and is measured in Megawatts (MW). Q is the power required to maintain the voltage levels necessary for active power to be delivered and is measured in volt-amperes reactive (VAR). The total energy generated by SPF and the conventional generators, measured in MWh, is calculated using equation below.

$$TE = \frac{1}{2}\sum_{t=0}^{m=48} P_t \tag{6}$$

where TE is the total energy in MWh and P_t is the power generated by the source in MW in time t for 24-hour recorded every 30 minutes. In a power grid, each bus (node) represents a connection point for generators, loads, or other buses. The goal of power flow analysis is to determine the voltage magnitude and phase angle at each bus, as well as the power flow on each transmission line. This information is crucial for the operation, control, and optimization of the power system [23].

3.4 CO_2 Emissions Avoidance Calculation

Using the power generated from SPF with the support of OSR can significantly reduce CO_2 emissions compared to conventional power generation based on fossil fuels. This reduction occurs because solar energy is a clean, renewable resource that does not produce direct CO_2 emissions when generating electricity, unlike coal, natural gas, or oil. The amount of CO_2 avoidance is typically calculated using the following general formula [24].

$$ACO2 = OSRsE * FCO2 \tag{7}$$

where ACO2 is the quantity of CO_2 emissions that have been avoided in ton CO_2/day, OSRsE is the amount of energy generated by the OSRs in GWh/day and the FCO2 is the generation emissions factor CO_2/kWh, which represents the amount of CO_2 emissions avoided per unit of electricity generated. This factor varies depending on the type of fossil fuel used and depending on the country. In this study, the generation emission factor for grid electricity is 0.20707 CO_2/kWh, which is an average that considers the mix of all energy sources used in the United Kingdom [25].

4 Results and Discussions

4.1 Enhanced SPF Generation with OSRs

The first key result of the study is the significant increase in SPF generation due to the use of OSRs. The simulation results showed that integrating OSRs with existing SPF leads to an additional daily energy output of 1.23 GWh. This increase is achieved by extending the effective hours of sunlight during dawn and dusk, when SPF produces minimal or zero power. Fig. 5 presents a comparative analysis of power generation for fossil fuel generators and a SPF enhanced by OSRs over 24 hours. It represents scenarios with different OSR contribution, 25%, 50%, 75%, and 100%. The horizontal axis denotes time in 30-minute intervals, while the vertical axis represents power output in MW. At 25% OSR, fossil fuel generation remains significant, though it gradually decreases as SPF output peaks. With a 50% OSR contribution, fossil fuel dependence lessens further, as SPF maintains higher output levels. At 75% OSR, fossil fuel usage is significantly reduced, with SPF nearly matching or surpassing it during peak periods. Finally, with 100% OSR, fossil fuel generation drops to minimal levels, with SPF effectively meeting nearly all energy demands during the dawn and dusk.

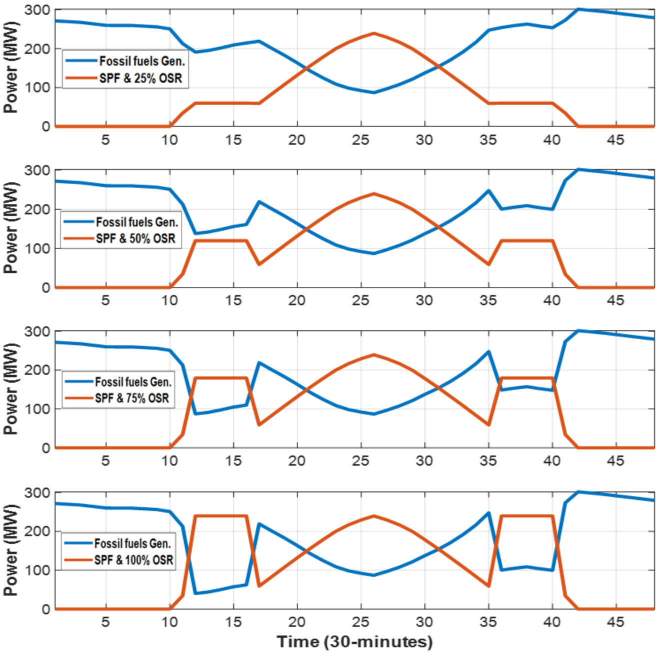

Fig. 5 Power output dynamics of fossil fuel generation, SPF and OSR

Fig. 6 illustrates the energy distribution across different sources of fossil fuel generators, SPFs, and OSRs at varying levels of OSR contribution, all while maintaining a constant load of 6.68 GWh. The SPF contribution remains constant at 1.48 GWh in all scenarios. Without any OSR contribution (0% OSR), the load is primarily met by fossil fuel generation (5.19 GWh), with SPF contributing 1.48 GWh. As the contribution of OSR increases to 25%, 50%, 75%, and 100%, fossil fuel generation gradually decreases from 5.19 GWh to 3.96 GWh, while the contribution of OSR increases from 0.33 GWh to 1.23 GWh. This demonstrates the effectiveness of OSRs in improving SPF generation and significantly reducing the need for fossil fuel-generated electricity.

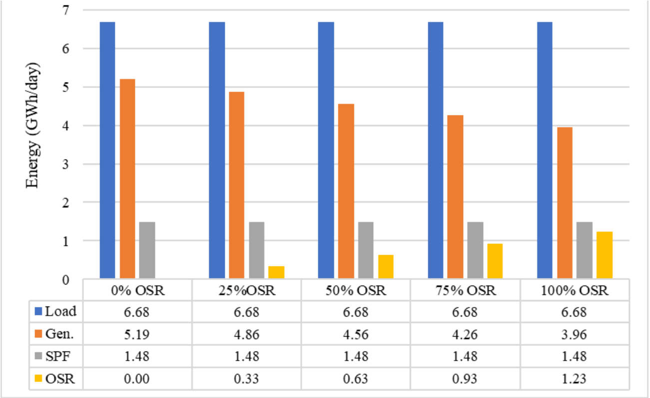

Fig. 6 Energy distribution across different OSR contributions in a SPF

4.2. Avoidance of CO2 Emissions with OSRs

OSRs contribute to a substantial reduction in CO_2 emissions through enhancing SPF generation. Fig. 7 illustrates the impact of different levels of OSR contribution on CO_2 emissions, showing both CO_2 produced by fossil fuel generators (in blue) and the CO_2 avoided by SPF and SPF (in orange) per day. Without OSR (0% OSR), the system produces 1.08 tons of CO_2 per day, with no CO_2 avoided. As the OSR contribution increases, CO_2 production gradually decreases, while CO_2 avoidance increases. For instance, at 25% OSR, CO_2 production drops to 1.01 tons, and 0.07 tons of CO_2 are avoided. At 50% OSR, CO_2 production is further reduced to 0.94 tons and 0.13 tons of CO_2 is avoided. When OSR contribution reaches 100%, CO_2 production decreases to 0.82 tons, while CO_2 avoidance reaches 0.26 tons. This result demonstrates the effectiveness of OSRs in reducing the dependence on fossil fuels, thus reducing carbon emissions by improving the efficiency of SPF generation.

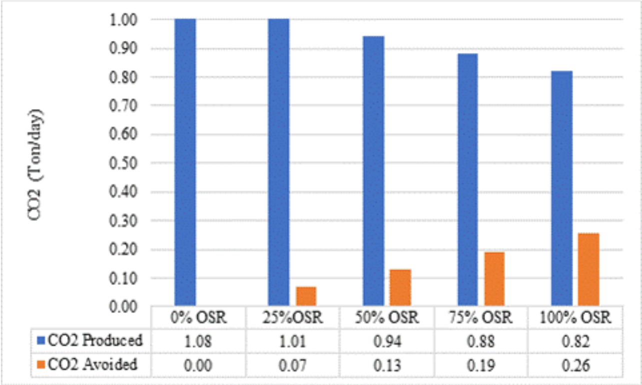

Fig. 7 CO_2 emissions reduction achieved through increasing OSR levels.

4.3. Grid Stability and Voltage Analysis

The power flow analysis conducted on the IEEE 9 bus system demonstrates that integrating the additional power generated by SPF with OSRs does not negatively impact grid stability. The voltage stability analysis shows that the voltage levels remained within acceptable limits for all buses, even under the enhanced power generation scenarios. This finding suggests that the integration of OSRs into the grid is technically feasible without compromising the reliability of the grid. Fig. 8 illustrates the voltage profile over time in a power system at different levels of OSR contribution. The horizontal axis represents time in 30-minute intervals (results reading taken every 30-minute for 24 hours), while the vertical axis shows voltage per unit (p.u). The curves represent scenarios without OSR (blue) and with OSR contributions at 25% (orange), 50% (yellow), 75% (purple), and 100% (green). The voltage profile without OSR shows the lowest overall levels, with significant dips and peaks indicating instability. As OSR contributions increase, the voltage profile stabilises and rises. With 25% OSR, there is a noticeable improvement, but the voltage still fluctuates. At 50% and 75% OSR, the voltage curve smooths out further, indicating better stability. With 100% OSR, the voltage remains at the highest and most stable level, showing that maximum OSR contribution significantly enhances voltage stability and overall system reliability. This highlights the effectiveness of OSRs in maintaining a stable voltage supply, thereby reducing the potential for power disturbances during dawn and dusk.

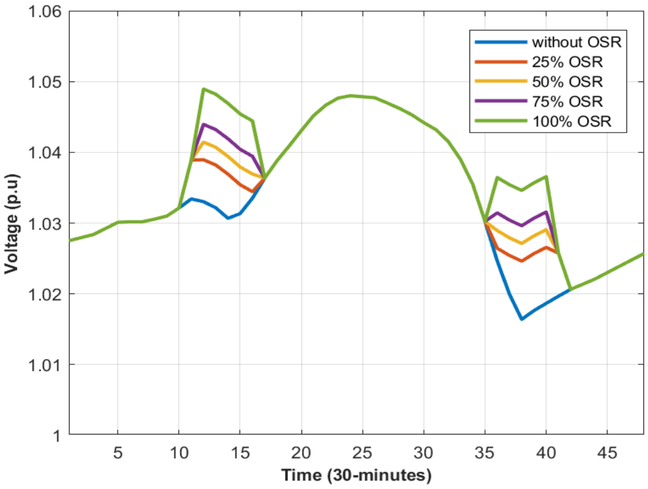

Fig. 8 Voltage profile of the IEEE 9 bus with the SPF and OSRs

4.4. Discussion

The results clearly indicate that OSRs can play a transformative role in the generation of solar energy. Compared to SPF, which are limited by the availability of direct sunlight, OSRs significantly enhance SPF energy output by utilising reflected sunlight during otherwise low-output periods. This not only increases the efficiency of SPF but also reduces the need for energy storage solutions [12], as the extended generation period better aligns with peak demand times. The CO_2 reduction achieved with OSRs highlights their potential as a key technology in the fight against climate change. OSRs contribute to a reduction in greenhouse gas emissions by displacing a significant amount of fossil fuel-generated electricity. This reduction is particularly impactful in regions where coal and natural gas dominate the energy mix. Furthermore, the use of OSRs aligns with global sustainability goals by promoting the adoption of cleaner, renewable energy sources.

Although the paper confirms the technical feasibility of integrating OSRs with SPF, it also brings to light several challenges. The deployment of OSRs requires in-space assembly, precise positioning and orbit control, which could involve significant technical and financial investments. Additionally, the launch and operation cost of reflectors and their impact on investment returns are important considerations that need to be addressed in future research. Nevertheless, as the reflector technology has already been demonstrated in space, the successful implementation of OSRs could open new avenues for SPF generation, particularly in regions with less direct sunlight or during seasons with shorter daylight hours. Furthermore, the principles behind OSRs could be adapted for use in other renewable energy applications, such as terrestrial concentrating solar power systems (CSP) or even in SBSP generation. However, to reach their full potential, continued research and development, along with supportive policy frameworks, will be essential.

5 Conclusion

This paper has demonstrated the considerable impact of incorporating the contributions of OSR in enhancing SPF energy generation, improving voltage stability, and reducing CO2 emissions in hybrid electrical grid systems that combine fossil fuel generators with SPF. As the OSR contribution increases, there is a significant reduction in reliance on fossil fuel generation, thereby increasing the utilization of solar energy. The simulations demonstrate that higher OSR levels not only improve the system's voltage profile but also lead to a substantial reduction in CO2 emissions. The findings underscore the considerable benefits of integrating OSRs into existing SPFs, revealing their potential to drive more sustainable and efficient energy systems. However, realising these benefits on a larger scale will require overcoming technical challenges and adopting sustainable deployment practices to ensure long-term success.

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