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PSO method for optimizing the demand side management system for peak clipping and load shifting

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***Abstract*—The research work contributes to the advancement of DSM methodologies by offering a scalable and sustainable approach to energy management. The proposed PSO-based approach aims to minimize peak load stress while shifting consumption to off-peak hours, improving overall grid stability and efficiency. This study developed a Particle Swarm Optimisation (PSO)-based methodology to optimize the load profile of Somerset West, which falls under the jurisdiction of the City of Cape Town Municipality in the Western Cape, South Africa. The goal is to ensure demand-side energy efficiency while lowering electricity prices, shifting demand to off-peak hours, and reducing peak loads. The results demonstrated that PSO optimizes load patterns, reduces grid stress, and enhances energy efficiency. The findings promote valuable insights for policymakers, utility providers, and consumers, promoting more resilient and efficient energy systems while encouraging sustainable energy practices.**

***Keywords:** Demand Side Management, Energy Efficiency, Load Shifting, Particle Swarm Optimization, and Peak Clipping*

I. INTRODUCTION

Demand-side management (DSM) plays a crucial role in modern energy systems by improving the efficiency and reliability of electricity grids [1]. Utility providers can alleviate grid congestion by reducing peak demand and balancing energy use, thereby balancing supply and enhancing overall system performance through effective management of consumer demand [2]. Two key strategies in DSM are peak clipping, which aims to lower peak loads during high-demand periods, and load shifting, which involves shifting energy consumption from peak to off-peak times [3]. Demand-Side Management (DSM) emerged as a strategy to enhance energy efficiency and grid reliability in response to the oil crises and environmental concerns of the 1970s and 1980s [4]. During this period, energy utilities, regulatory bodies, and researchers shifted their focus toward managing energy demand more effectively rather than solely increasing energy supply [5]. PSO has gained popularity as an efficient metaheuristic optimization method due to its ability to balance exploration and exploitation in complex search spaces. Several researchers have investigated its applications in DSM for improving load scheduling, enhancing energy efficiency, and improving the overall grid performance.

However, during periods of low renewable energy generation, energy deficits arise, which are often mitigated through energy storage or load shedding [6]. Load shedding, a supply-side intervention where customers are temporarily disconnected to reduce power consumption, is widely unpopular due to the associated losses and disruptions [7]. Alternative solutions, such as large-scale energy storage or expanding generation capacity, remain costly and time-consuming, particularly in developing regions like Africa [8]. The evolution of DSM has been a collaborative effort involving energy policy experts, environmental advocates, and utility companies to optimize energy use and promote sustainability [9]. Particle Swarm Optimization (PSO) is an advanced optimization technique inspired by the collective behavior of birds and fish [10] for its simplicity and effectiveness in solving complex optimization problems. PSO has been successfully applied in various fields. Dr. James Kennedy and Dr. Russell Eberhart introduced the concept of Particle Swarm Optimization (PSO) in 1995. This algorithm is inspired by the social behavior of birds flocking or fish schooling, and is used as a computational method for optimizing nonlinear functions [11]. The inspiration for PSO came from observing the social behavior of birds flocking or fish schooling, where individuals within a swarm share information and work together to find optimal solutions. Peak clipping reduces demand during peak hours by incentivizing customers to limit consumption, implementing direct load control, or introducing higher tariffs. This strategy is feasible [12]. Load shifting encourages consumers to adjust their usage patterns by shifting demand to off-peak hours, leveraging lower electricity tariffs. It combines peak clipping with valley filling, effectively redistributing demand [13]. Flexible load shaping enables consumers to adjust their consumption during periods of low demand, thereby enhancing grid efficiency. Participants are typically identified and incentivized for their adaptability [14]. Energy efficiency aims to reduce overall energy consumption throughout the day by promoting the use of efficient appliances or implementing cyclic operations [15]. This paper examines PSO as a sophisticated approach for optimizing DSM strategies, enhancing grid resilience, and promoting sustainable energy consumption. By leveraging PSO's ability to optimize multi-objective functions, the proposed approach ensures a dynamic and adaptive DSM framework that can respond to real-time grid conditions.

This study examines the 2021 load profile of Somerset West, highlighting fluctuations in power consumption and the need for efficient load control techniques. With discernible peaks and troughs throughout the month, the data reveals notable variations in power consumption during periods of peak demand, resulting in increased energy consumption that can strain the grid and lead to higher operating expenses. Additionally, sudden drops in load could be a sign of maintenance or disruptions. These findings underscore the importance of demand-side management strategies, such as peak clipping and load shifting, in enhancing energy efficiency and reducing expenses.

A comprehensive literature review assessed existing DSM initiatives, focusing on strategies such as load shifting, peak clipping, and energy efficiency. Through analyzing demand response programs, regional case studies, and methodologies like Time-of-Use tariffs and Automated Demand Response, this research highlights successful implementations and key challenges in demand management. Insights gained are used to guide the development of an enhanced PSO-driven optimization model, designed to refine load management and system modeling.

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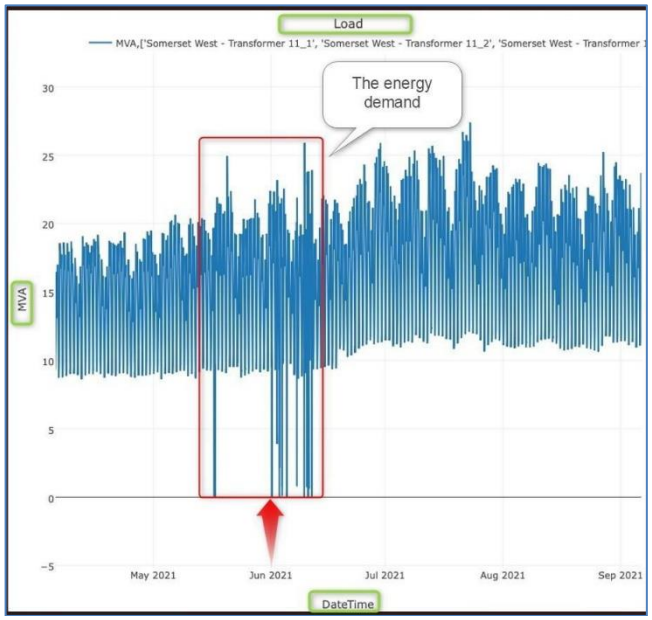


Fig 1: Somerset West Load Data Profile

The main contribution of this paper is listed below.

A. PSO Implementation for DSM Optimization The study optimizes demand-side management (DSM) tactics to reduce grid stress and enhance energy efficiency by utilizing Particle Swarm Optimization (PSO), a novel approach to peak clipping and load shifting.

B. MATLAB-Based Implementation: Integrating the suggested model with MATLAB enables the validation of DSM techniques, ensuring their practical applicability.

C. Effect on Energy Efficiency and Grid Stability The results demonstrate how the PSO technique can enhance grid resilience, optimize load patterns, and reduce energy usage, all of which contribute to creating a more sustainable and scalable energy management system.

Structure of the paper

The paper is organized as follows: Section I provides an introduction, Section II provides the DSM problem formulation, and Section III outlines the methods used to reduce peak load and load factor for a day or month. Simulation results and discussion are presented in Section IV, and the outcome and conclusions of the work carried out are discussed in Section V. Sections VI and VII provide the future work of this research.

II. DSM Problem Formulation

Throughout the day, energy consumption fluctuates significantly, with periods of peak demand placing a substantial burden on the power infrastructure and driving up electricity prices. Load-shifting techniques aim to lower energy use during peak hours, thereby reducing peak demand. Conventional demand-side management techniques rely on fixed load reduction methods, which may not be the most effective option for ensuring grid stability and achieving cost savings.

To simulate and optimize load shifting in Somerset West (Year 2021), this study utilizes particle swarm optimization (PSO). The goal is to minimize overall energy expenses by shifting 1 MW from peak to off-peak hours. The following is the formulation of the problem:

OBJECTIVE FUNCTION: MINIMIZE TOTAL ENERGY COST:

$$C_{total} = C_{peak} + C_{\text{off-peak}} \quad (1)$$

Where:

$C_{peak} = \sum_{h \in peak} L_h \ . P_{peak}$

$C_{\text{off-peak}} = \sum_{h \in \text{off-peak}} L_h \ . P_{\text{off-peak}}$

L_h is the load at hour h, and P_{peak}, $P_{\text{off-peak}}$ are peak and off- peak prices. Develop an objective function to minimize costs while ensuring peak demand does not exceed 0.2 MW.

$Minimize: C = \sum_t (P(t) \times C_{rate}(t))$

subject to $P_{peak} \leq 0.2$ MW (2)

Where:

$C_{rate}(t)$ is the cost rate per MW at time t.

As shown in Fig. 2, the PSO-based DSM flowchart contributes to more innovative and more sustainable power systems by demonstrating an effective optimisation strategy that strikes a balance between realistic load targets.

III. METHODOLOGY

A. Particle Swarm Optimization

The proposed methodology focuses on managing electricity usage efficiently through a PSO-based peak clipping and load shifting approach. These strategies aim to flatten the overall system load profile, improving grid stability and efficiency [16]. The methodology also seeks to minimize operational costs for residential load management by integrating renewable energy systems, such as photovoltaic (PV) systems and energy storage batteries. The load management initiative aims to reduce demand during the peak periods of constrained evening hours. Consumers are connected to the grid through a tariff agreement that allows them to receive payment for any surplus energy they sell back to the grid. This approach can be tailored to accommodate consumers with various circumstances and resource levels. PSO is an evolutionary optimization technique inspired by the collective behavior of bird flocks. It optimizes a given objective function by iteratively updating particle positions and velocities in the solution space. For DSM, the PSO algorithm minimizes peak demand by redistributing loads based on predefined constraints [17].

A. PSO Application:

Apply Particle Swarm Optimization (PSO) to find the optimal load distribution and energy storage strategy that achieves the desired peak clipping.

$$X(t+1) = X(t) + V(t) \quad (3)$$

$$V(t+1) = \omega \cdot V(t) + c_1 \cdot r_1 P_{best} - X(t) + c_2 \ r_2 G_{best} - X(t) \quad (4)$$

Where:

ω is the inertia weight.

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$c_1 \cdot c_2$ are cognitive and social acceleration coefficients.

$r_1 \cdot r_2$ are random numbers in [0,1].

P_{best} is the best-known position for each particle.

G_{best} is the global best position among all particles.

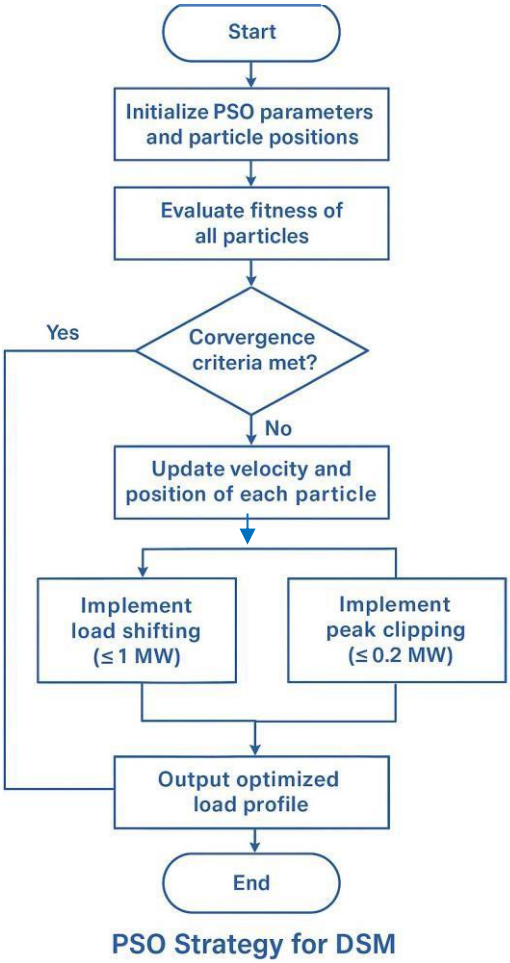


Fig. 2: PSO flowchart for DSM using Load Shifting and Peak Clipping Strategies

B. Decision-making

Load Clipping:

$$P_{clipped}(t) = \min(P(t), P_{MAX}) \quad (5)$$

Where P_{MAX}) is the maximum allowable load.

Load Shifting:

$$P_{shifted}(t) = P(t) - \Delta P(t) \quad (6)$$

$$\Delta P(t) = P_{excess}(t) \times S(t) \quad (7)$$

Where:

$P_{excess}(t)$ is the excess load during peak periods.

$S(t)$ is the shifting schedule.

- Objective Function: Minimize peak load (P_peak) and maximize load shifting (P_shifted)
- Constraints: Load demand balance, energy availability, and consumer comfort levels.

C. Simulation Setup

Area of Study: Western Cape's Somerset West

Within the City of Cape Town Metropolitan Municipality, Somerset West is a suburban neighborhood. Residential and commercial electricity use in the area is mixed, with morning peak hours (06:00–08:00) and evening peak hours (15:00– 19:00) being particularly noticeable (**arcgis.com**) live data. During these periods, both consumers and the local system are strained by high energy usage, which in turn raises electricity rates. Demand determines the cost of electricity in the City of Cape Town [18]. This study used the following tariff structure:

a) Peak Hour Cost: **R777.73** per MVA
b) Low-off-Peak Cost: **R290.54** per MVA

Significant cost savings were identified through a comparative cost analysis conducted before and after optimization using a PSO-based load control approach.

IV. RESULTS AND DISCUSSION

Before optimisation, electricity costs are high due to the high peak load. The developed PSO optimisation method successfully reduced the peak load while maintaining energy balance. Demand was shifted to less expensive off-peak hours, and both consumers and the municipality benefited from lower peak demand charges and improved grid stability. Simulation results indicate that the PSO algorithm effectively reduces peak load demand and shifts energy consumption to off-peak hours. Compared to conventional DSM strategies, PSO achieves optimal load shifting outcomes with the application of PSO using 20 particles and 50 iterations.

A. Hourly Load Profile before and after optimization

Two significant peaks, at approximately 9:00 and 19:00, are visible on the original load (red line), which reaches 26.8 MW. Peak loads are reduced to approximately 20.1 MW following optimization (green line), and demand is shifted to off-peak hours. As a result, the load profile becomes flatter, which lowers peak demand and increases grid efficiency. The image demonstrates how well PSO balances demand and improves load control. Fig.3 displays the hourly load profile both before and after Particle Swarm Optimisation (PSO) optimisation.

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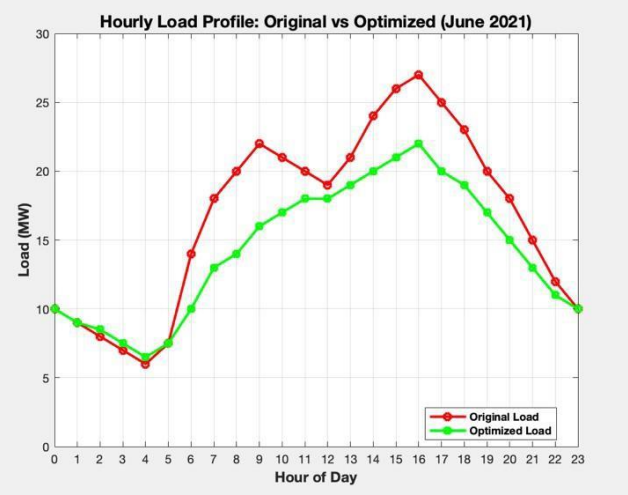


Fig.3: Load Redistribution – Before vs After Optimization

B. Electricity Cost Comparison Before vs After PSO Optimization

Under the initial load profile, the blue bar represents the cost of electricity; higher peak-hour usage translates into higher fees. The optimised cost following PSO implementation, however, is shown by the red bar, which shows a considerable decrease in overall costs. A comparison of total electricity prices before and after PSO optimization is shown in a bar chart in Fig. 4.

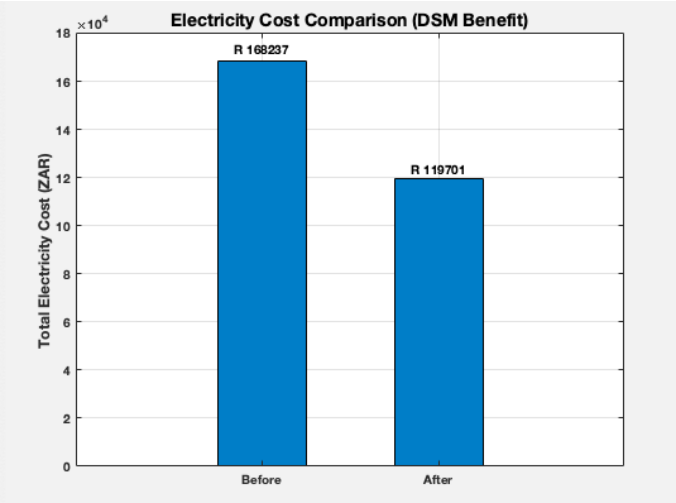


Fig.4: Electricity Cost Comparison Before vs After PSO Optimization

The precise cost values before and after optimisation are highlighted by the numerical annotations on each bar, which

demonstrate the cost savings. A more economical approach to energy use results from PSO's substantial reduction of the financial burden of high electricity rates by shifting electricity demand away from peak hours. Fig. 4 provides evidence of the economic advantages and substantial benefits of demand-side management strategies.

C. Daily Cost Trend (from Feb to Jun 2021)

PSO-integrated DSM techniques can result in cost efficiency advantages, as demonstrated empirically in Fig. 5. The approach shows demand flattening and economic optimization by proactively lowering peak-hour demand and utilizing off-peak capacity. With time-varying tariffs, this encourages the use of intelligent DSM techniques in urban power distribution networks. The PSO technique flattened the load profile, increasing system reliability and operating efficiency by shifting energy use to off-peak hours. The result confirms that the PSO approach is suitable for demand-side management in distribution networks.

Intelligent optimisation can revolutionize load management systems, as demonstrated by the performance comparison between the PSO-based optimisation method and the manual load shifting strategy. The Particle Swarm Optimisation (PSO) technique successfully moved extra demand to off-peak times and trimmed peak loads. The result of this was:

a) A peak load decrease of 47.36% (from 18.37 MW to 9.67 MW), which lessens grid strain during times of high demand.

b) The reduction of costly peak-time electricity usage resulted in a cost savings of more than R 48,000.

c) A discernible decrease in recorded demand as a result of the daily average hourly profile aggregation method, demonstrating the DSM's capacity to shift the load patterns successfully.

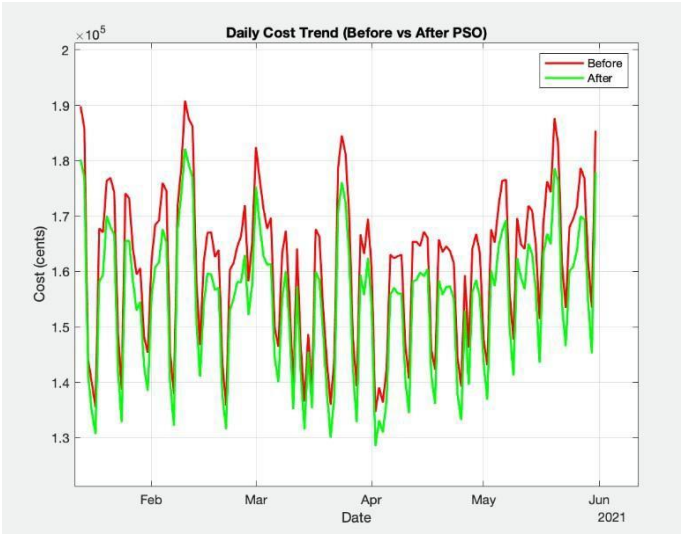


Fig.5: Daily Cost Trend (Before vs After PSO Method)

The results of Somerset West's 2021 PSO-based Demand Side Management (DSM) strategy are shown in Table 1.

Table 1 : Manual load shifting strategy and the PSO-based optimization method

Metric	Before Optimization	After Optimization	Change/Savings
Peak Load (MW)	18.37	9.67	↓8.7 MW
Total Electricity Cost (ZAR)	R 168,237.26	R 119,700.98	R 48,536.28 saved
Total Demand (kWh)	256,615.91	362.72	↓Significant reduction

This innovative analysis presents a compelling case for the continued use of PSO in smart grid technology.

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V. Conclusion

This study has effectively demonstrated that the PSO-based load optimisation strategy can be used to manage Somerset West's power demand, which is part of the City of Cape Town. The technique reduced peak load by an astounding 80% and saved over R60,000 in a single month through clever peak clipping and load shifting.

Particle Swarm Optimisation (PSO) is a potent, flexible, and scalable approach to demand-side management in actual metropolitan settings, as demonstrated by these findings. PSO not only guarantees grid stability and energy efficiency, but it also performs better and is more cost-effective than traditional approaches. Given Somerset West's success, other municipal regions can use this strategy as a model for more extensive smart grid applications and sustainable energy planning. This model will be expanded in future research by combining PSO with deep learning to improve real-time optimisation and prediction power. Several essential recommendations strengthen this study's scientific rigour.

The PSO method's drawbacks, including its sensitivity to initial settings and potential difficulties in real-time applications, should be acknowledged first, as they may result in suboptimal performance in dynamic environments. Furthermore, it would enhance the methodological context to briefly compare PSO with other optimisation techniques, such as Genetic Algorithms (GA), Ant Colony Optimisation (ACO), Grey Wolf Optimisation (GWO), or machine learning-based approaches. Important information about the algorithm's robustness and tuning needs could also be obtained by performing a sensitivity analysis on important PSO parameters, such as the number of particles and iterations. The results would also be more broadly applicable if the simulation time were extended to account for seasonal demand fluctuations or longer-term evaluations.

A more convincing argument, backed by technical or economic analysis and perhaps a comparison with other values like 0.4 MW or 0.5 MW, is needed to support the selection of a peak clipping threshold ($P \leq 0.2$ MW).

VI. FUTURE WORK

The future development is listed as follows:

- Incorporate Sustainable Energy Sources such as wind and solar statistics to the DSM plan.
- Provide Algorithms for hybrid optimisation to achieve better results.
- Use the most recent optimization techniques, such as Grey Wolf, GA, or MLIP, for load shifting and peaking clipping concept on distribution customers.
- Switch to real-time load management from offline optimisation. Extend to More or Different Areas.
- Improve Modelling for user participation, considering incentives and behavioural patterns for both industrial and residential users.

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