Maximizing Energy Efficiency in Energy Management System using Optimization Algorithm in Microgrids

by

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University of Victoria

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Abstract

Due to technological advancements, population growth, and urbanization, the demand for electricity is increasing day by day. Meeting the global electricity demand is a challenge considering its socio-economic and environmental impacts. Energy Management Systems (EMS) are becoming a vital topic of discussion, as renewable energy sources such as solar, wind, hydro, and energy storage systems are being considered. EMS is becoming an essential component of a microgrid, as the system works when connected with the grid and also in islanded mode, connected with renewable sources. However, the increasing use of renewable energy resources is causing operational efficiency and reliability issues. Additionally, meeting demands during high energy consumption and reducing costs during high demand for electricity are challenging. Therefore, optimization techniques are being implemented to solve issues related to demand response and cost reduction. The proposed approach focuses on minimizing the total cost of energy consumption, taking into account demand, load control, energy storage systems, and PV systems using the novel algorithm Ant Colony Optimization. The results demonstrate that the Ant Colony Optimization algorithm is effective in reducing costs and can be used to address increasing demands and constraints related to energy management in microgrids. Future work may include fault detection, power quality improvement through optimization algorithms in the real-world grid model, and automating it to prevent losses, power outages, and asset failures.

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Nomenclature

ACO: Ant Colony Optimization

DER: Distributed Energy Resources

ECC: Energy Control Centre

DMS: Distribution Management Systems

EMS: Energy Management System

ESS: Energy Storage Systems

ISO: International organization for Standardization

Microgrids: Small scale electricity network connecting consumers to an electric supply

Pheromone: Probability distribution of different components of the solution to be modelled

PV: Photovoltaic

RES: Renewable Energy Sources

SCADA: Supervisory Control and Data acquisition system

SOC: State of Charge

VPP: Virtual power plant

Acknowledgement

I would like to express my gratitude to the world around me for their support and encouragement in telling me that life is a journey and to embrace it.

I am deeply thankful to Lord Krishna for His countless blessings and for encouraging me to go and achieve my dreams.

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In the words of Robert Brault, "enjoy the little things in life, for one day you may look back and realize they were the big things".

Dedication

My amazing parents

1. Introduction

1.1 Context

Distributed energy resources (DER) and a number of loads, when interconnected with each other with a single communication and control unit that can connect with the grid and be operational in island mode or independently, are called a microgrid. Microgrids are a part of the smart grid as the utility system is connected upstream with the main distribution system [1]. Microgrids contain dispatchable loads, non-dispatchable loads, conventional sources of energy, non-conventional sources of energy such as solar, wind, hydro energy, nuclear energy biomass, and storage devices such as batteries. The utility equipment in this hybrid or island model stays the same as in the main grid, but the rating as well as the amount of assets reduce.

Microgrid, or island grid, is a part of the smart grid and solves social, economic, and environmental constraints. But infrastructure development and the efficiency of renewable sources have been challenges. Microgrids rely on renewable sources, but switching to the grid and isolating from the grid continuously leads to fluctuations, issues with power quality, problems with user demands, uncertainty with assets, deviations in supply and demand of electricity, etc. Additionally, it causes reliability issues due to uncertainty with solar and wind sources, considering constraints related to the environment and weather [2]. This leads to instability in the microgrid and may not meet end-user demand. These problems can be solved by an energy storage system or battery management system (ESS).

Amalgamating energy storage systems, renewable energy sources, different loads, and grid connections increases complexity and can cause instability, which leads to serious deviations with the power factor component. Power factor imbalance causes an increase in cost and leads to an increase in electricity consumption, leading to a compromise with power quality. An optimisation algorithm can be a decision-maker to meet the power demands, reduce the energy consumption, decrease the cost, and reduce the losses. In this report, we execute an energy management system model and implement the Ant Colony optimisation algorithm, which acts as a solution to overcome the above-mentioned challenges in order to achieve optimal results. Through ACO, the report focuses on cost reduction in the model and showcases different trends in cost, consumption, storage, and load demand. The proposed framework can also be applied for fault detection and power quality improvement for future expansion.

1.2 Objectives

Microgrids are considered a component of the smart grid and are really vital in the modern world to meet energy demand. Conventional sources of energy, dispatchable loads, non-dispatchable loads, and battery systems are all part of a microgrid. The number of components makes the system heterogeneous but makes it highly reliable and efficient [3]. Considering environmental and socio-economic factors and the uncertainty in the electrical grid, an energy management system model is developed. The EMS model can manage the demand for electricity and focus on energy savings by reducing the cost.

The proposed approach here is to develop an energy management system model integrated with different kinds of parameters for loads, energy sources, and batteries. Implementation of an optimisation algorithm in the model will increase efficiency and focus on reducing costs. The objectives of this model are to focus on peak demand shifting through energy storage systems through load shedding or load shifting. Other objectives include the implementation of ant colony optimisation into the energy management system model, identifying the parameters that affect the cost of electricity, maximising the efficiency of the model by constantly maintaining or reducing the cost of energy, analysing the grid usage to determine the cost per unit of electricity through simulation, and proposing recommendations for implementing the optimisation algorithm for the real-world grid.

1.3 Report Outline

This report aims at investigating the optimal solution for the energy management system model (EMS) through the implementation of an optimisation algorithm. Chapter 2 provides background by highlighting the concept of an energy management system, what a microgrid is and how it works, battery storage or energy storage systems, how load shifting and load shedding occur when demand increases and decreases, and the optimisation algorithm for microgrids. Chapter 3 discusses the model used for this project, how an ant colony optimisation algorithm is developed for the model, and the problems and limitations with the model that can be solved. Chapter 4 shows the implementation of the ant colony optimisation algorithm in the model as well as discusses the results. The report concludes with final remarks and future scopes in chapter 5.

2. Background

2.1 Energy Management System

The era of energy management systems started in the decade of 1960, when the term "control centre" was coined. Later on, after a decade, when a transition came with technology, it was called the Energy Control Centre (ECC). In the 1990s, when the trend of supervisory control and data acquisition systems (SCADA) came to the market, it was called SCADA-EMS. Finally, when technology started to take an upward trend, EMS and SCADA were coined as two separate terms, and by the end of the 1990s, the term "energy management system" had trended around the world [4]. When real-time systems were merged with electrical utility and distribution systems, different types of methods, such as demand-side management, load control, and distribution management systems (DMS), were merged with the EMS.

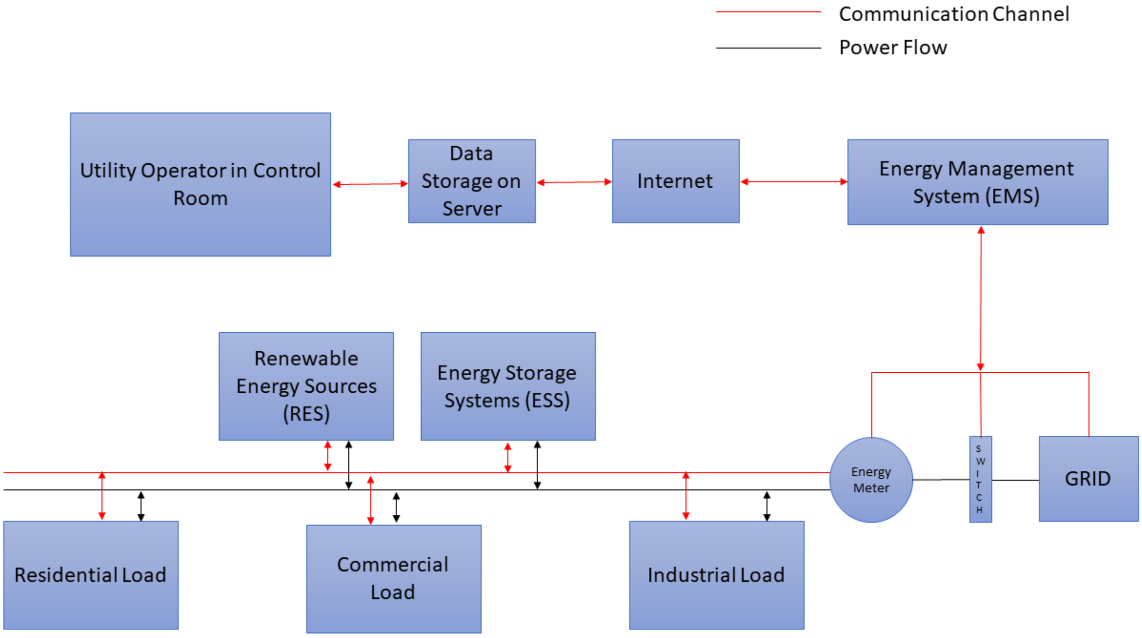

Figure 1 Energy Management System Model

Several factors, such as social, economic, and environmental factors, play a huge role as EMS is meant to save costs with the electricity distribution as well as take vital and timely decisions on energy savings [4]. The objectives of an energy management system are:

- To control the flow of power from the main grid.
- To take smart decisions on the demand and supply of electricity into the microgrid.
- Maximise the efficiency of the grid.
- To consume more power from renewable energy sources (RES) such that the cost of energy from the grid upstream is low and the model follows the target of environmental sustainability.
- To convert the microgrid into island mode without affecting operations when there is a failure with the main grid.

The functioning and scope of work of EMS include [5] and [6]:

- Power generation, power transmission, and power distribution planning
- Managing the Network: Power Scheduling, Minimising Power Losses, and Control of Power Operations The topology depends on load estimation, dispatch, planning, and operational constraints.
- Managing the power generation: managing the load, managing the fuel for generation, managing the resources for generation, controlling voltage, current, frequency, and power factor control
- Power performance evaluation and quality control
- Identify the faults in real time, notify the operator, and transmit signals for troubleshooting.
- Demand Forecasting: It is in the scope of EMS as it helps to forecast the demand by creating a graph for upcoming days and how the electricity requirement will have to be satisfied. This helps to arrange resources, maintenance of equipment, cost evaluation, etc.
- Energy and cost savings: The model can detect the optimal solution for satisfying the demand at a low cost. Additionally, it can also forecast demand for upcoming days and then assist the decision-makers in intraday trading, or buying and selling of electricity.

Minimises the Outage Duration: The EMS model has the potential to detect future outages or faults and can suggest outcomes to eliminate outages and prevent downtime.

The advantages and disadvantages of the EMS are highlighted below:

Advantages	**Disadvantages**
A utility or a distribution company stays in Compliance	Can cause system failure
Risk Management	More complexity in the system
Efficient and faulty equipment or system can be detected	More operational cost
Real-time data and operations are feasible	Satisfying the criteria of data analytics, cyber security- Technological Risks
Provides Environmentally Sustainable solution	Entire system can fail or malfunction due to sensors and automatic systems
Energy Stability	Requires timely technical upgradation
Economical Solutions	Initial investment to setup the system is expensive
Can be expanded to small scale system when entire central system is under the same model	Can not be implemented in small scale distribution due to cost, operations
	More frequent preventive maintenance, and inspection needs to be done

Table 1 Advantages and Disadvantages of an Energy Management System model in real world [4]

The energy management system can be implemented on a large scale in a smart grid and then expanded to a microgrid model or an island grid. For EMS, policy, information, and data are most important. Information gathering, data retrieval, and data analytics are implemented into utility or distribution company software, which helps operations on a day-to-day basis. The scope of information depends on the number of equipment, flow of electricity, outages, control systems, instrumentation sensors, automation trends or data charts, data for reporting, frequent failures and maintenance required, etc. There are certain variables defined for the equipment and sensors connected to them. The sensor transmits a signal as required information, and that helps the energy management system take decisions. The last phase of the energy management system is maximising the energy efficiency through management practises according to ISO 50001. Energy management systems also include a review of energy use, establishing targets, identifying objectives, creating an action plan and steps to implement it, evaluating the performance, monitoring the performance on a daily basis, and reporting it to authorities. Hence, a structured format to follow the EMS is highlighted by ISO 50001 to maintain regulations and stay in compliance [7] [8].

2.2 Concept of Microgrids

When distributed sources, including conventional and nonconventional energy sources, dispatchable loads, non-dispatchable loads, and energy storage systems, act as a single unit that can be controlled and run in one model, then it is called a microgrid. Microgrid can run in grid-connected mode and in island mode. Microgrid is more precisely defined by the US Department of Energy, which states that it is "a group of interconnected loads and distributed energy resources (DERs) within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected and island modes" [4].

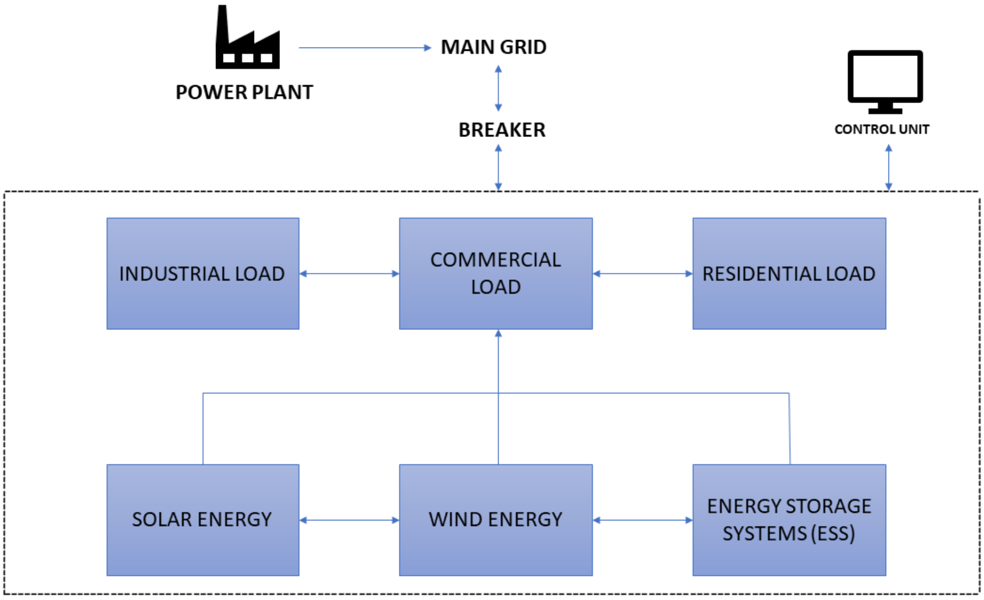

Figure 2 Model of Microgrid with Grid connected and Islanded Mode

The power plant generates electricity, which is distributed to the main grid. The main grid keeps on distributing electricity unless there is a fault and it is converted to island mode through a breaking or switching mechanism. Thus, a microgrid can be operated in grid-connected or island-connected modes. Both types of mechanisms can generate, distribute, and regulate the power flow. Microgrids can be classified into community microgrids, island microgrids, commercial and industrial microgrids, and military microgrids, which focus on reliability. According to the topologies of microgrids, they are converted to AC microgrids, DC microgrids, and hybrid microgrids. On the basis of applications, they are classified into rural microgrids and urban microgrids [9].

Microgrids are a part of grids, and they are called components of smart grids, but there are some similarities and differences between a main grid and a microgrid. The similarities are as follows:

- A grid or a microgrid both incorporate the same sources of energy.
- They both require transmission lines and power system equipment to distribute electricity.
- Both can be controlled, monitored, and regulated.
- Maintenance is required for both systems.
- The role of sustainability is to be fulfilled on both a small and large scale.
- Energy savings or reductions in energy consumption can be implemented in both systems.

The differences between the two is as follows:

Main Grid	Microgrid
They are large scale systems; they distribute electricity to other grids or microgrids or small power distribution areas	They are small scale systems; power is distributed to several microgrids. Microgrids are capable to run in islanded mode in case of grid failure
Main grid can be owned by a single organization or a single company	Microgrid are divided into several areas and with multiple microgrids, it can be owned by multiple organizations
There can be entire grid failure in case if there is an equipment failure, power outage	Microgrid is sustainable in case of power outage or grid failure as it gets converted to islanded mode
Main grid or traditional grid relies heavily on non-conventional sources of energy	Microgrids relies on conventional sources of energy and are environmentally sustainable
They are complex and need more maintenance, infrastructure development	They are small systems with less infrastructure and hence requires less maintenance
The distribution of power from one unit to other unit takes lot of power and hence more losses	The distance is less and it undergoes less transmission and distribution losses.
The cost of maintenance is more as there are a greater number of assets to manage	The cost of microgrid is less compared to traditional grid due to less complexity
Traditional Grids are tended to be less technological advanced due to interconnection of equipment's and cannot be upgraded easily	Microgrid can be upgraded easily, any innovations or technological advancement can be implemented quickly.

Table 2 Differences between traditional Grid and Microgrid

Thus, microgrids are a part of the traditional grid, but they hold a huge amount of importance as the pros outweigh the cons. The elements of microgrids are discussed in the next section of the report.

2.3 Design and Elements of Microgrid: Source, Renewable Energy Sources (RES) and Energy Storage Systems (ESS)

The microgrid structure or design varies based on geography, applications, resources, area, and several other factors. They can be centralised or decentralised with their control structure. For the microgrid design, we need to calculate demand, generation capability, and the total amount of equipment to be used, monitored, and controlled. Based on that, a microgrid can be designed and an energy management system can be implemented. According to the structure and design presented in this report, the microgrid system consists of the following components or elements: [4], [10], and [11].

1) Distributed Generators: The generation of power can be done by diesel-powered generators, coal-powered plants, hydropower plants, solar power plants, nuclear power plants, wind energy, and other sources. Renewable energy sources are used for clean and efficient energy. The generators generate the electricity and maintain the power factor, load factor, voltage, frequency, and all the necessary parameters. Distributed generators, like diesel generators or coal-powered generators, can increase the stability of the power system and can help during an uncertainty or a major outage. With the source of electricity or generation of electricity, the cost of operation and maintenance are also considered. DERs can transmit power locally, which saves on the cost of transmission and operation and reduces losses. It also improves stability and resilience on the grid, as the combination of conventional and non-conventional sources of generation can keep the grid balanced. While designing the microgrid, these parameters are taken care of so that it helps to select the correct source with specifications.

2) Energy Storage Systems (ESS): ESS are critical and crucial for microgrids as they act as a backup energy source acting between distributed energy resources and loads. When the demand is high, the ESS distributes power to the grid, but when the demand is low, the ESS is charged from the grid as well as from renewable energy sources such as wind, solar, etc. ESS helps to increase the stability of the grid and its efficiency. ESS can vary based on the size of the microgrid, as their capacity depends on the load requirements according to the calculations done during the design stage. Due to their efficiency, accessibility, and compactness, lithium-ion batteries are considered for ESS. Flywheel systems or hydro storage systems are considered for grids where the requirement for power is higher, as flywheel and hydro storage systems have a high amount of energy density. Automatic switching is done between the ESS, microgrid, controllers, and power converters when the microgrid senses a system outage, grid failure, or system failure.

3) Utility Connection: A utility connection is an interconnection between the main grid and the microgrid. With the concept of bi-directional power flow, utility connections can take power from the grid and supply power to the grid from a microgrid when required. A utility connection is required in these two types of cases. The first case is when there is a fault in the main grid and when a microgrid is isolated or converted to island mode. When there is a grid failure, the utility point of connection disconnects the microgrid from the grid and does a switching operation. The second case is when the demand increases in the microgrid and the main grid supplies power to the microgrid to fulfil the demand. Even for maintenance purposes, proper design, connection, installation, and operation are necessary so that both the microgrid and the main grid are reliable and efficient.

4) Loads: The loads are divided into two parts: dispatchable loads and non-dispatchable loads. Dispatchable loads can be turned on or off depending on demand. If the demand for electricity is higher, then non-essential or dispatchable loads can be turned off. A dispatchable load is also called a fixed load or a non-critical load. On the other end, non-dispatchable loads should always be kept on, as they are highly critical for operations. If renewable energy sources and energy storage systems are turned off, that means the microgrid will be down. Non-dispatchable loads maintain the constant power flow in the grid. Meanwhile, the dispatchable loads are used to make the system flexible, reliable, and efficient.

2.4 Demand Side Management Strategies: Load Shifting, Load Shedding, Demand energy response

Demand-side management is used by distribution companies to do smart electricity management. Demand-side management is used by distribution companies to satisfy the demand of customers during peak demand and off-peak periods. This also balances the power in the entire grid, helps forecast the load demand for the upcoming weeks and months, and helps calculate the cost of resources and materials. Demand-side management also focuses on load shedding, load shifting, and demand energy response.

The energy trading market keeps changing every day. Distribution companies decide based on side management where and when to buy the electricity from such that it gives an advantage and profits to their customers. Additionally, there are some rebates offered to customers for signing the demand energy response rebate form. During peak hours, those customers utilise electricity minimally or up to a certain set point. For the same reason, they get rebates from the distribution company. This also helps to reduce carbon footprints and reduces customers' electricity bills. Demand-side management can be done by techniques like load shedding and load shifting. As per [12], demand-side management is divided into increasing efficiency as well as giving a response on the grid during off-peak and peak hours. Such decisions are based on reliability, economics, social (who can get affected), and environmental (reducing carbon footprints). This helps the distribution companies make decisions on energy market trading. The classification of demand-side management in terms of energy management systems is described below [13].

Load Shedding: When demand for electricity exceeds supply and all the renewable energy resources along with energy storage systems are exhausted, load shedding is used. Load shedding is used only when it needs to be done in an emergency. This happens when the sources are turned off, and this can fulfil the demand for essential loads and ensure that the system doesn’t shut down or there is a blackout. During load shedding, emergency and essential loads are considered such that they get their power. They are implemented by switches, control systems, isolation systems, etc. It is also implemented considering the implications as well as according to the demand energy response rebate form consented to by the customer for essential loads.

Load Shifting: During excess demand, electricity can be taken from renewable energy sources or energy storage systems to fulfil the demand; during low demand, the electricity is stored. As per the figure, when, during a certain time of the day, demand increases, that is when load shifting takes place. The increase in demand was already forecast earlier, and that helps shift the loads in a timely manner. When load shifting is done timely, the load can be distributed or consumed accordingly.

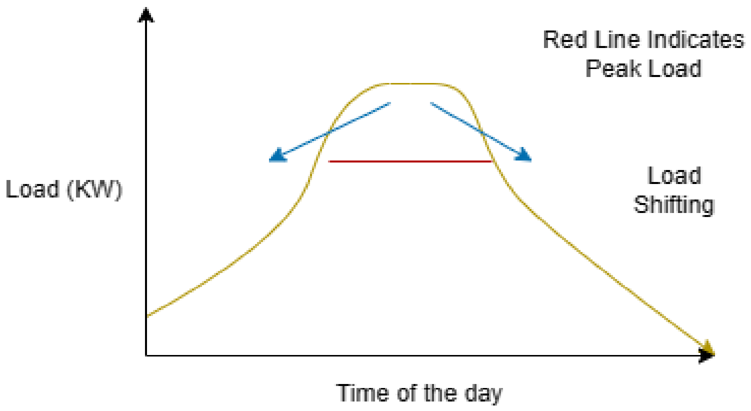

Figure 3 Load shifting pattern during a time of the day [14]

2.5 Optimization Algorithms for Energy Management in Microgrids

1) Microgrids in energy management systems have challenges like balancing supply and demand, grid stability, energy savings, cost, constraints of weather, and parameters with equipment. The energy management system model consists of algorithms and different sensors that send signals to different equipment in the model. The data is fetched from the equipment in real time, analysed, and sent to a simulator for simulation, where all the mathematical calculations are done to take decisions related to energy and cost savings. The simulator analyses the data and recommends optimised solutions. There are different optimisation algorithms in microgrids, and each one is used for different purposes [2] [15]

2) Linear Programming: Linear programming calculates how the number of resources for energy generation can be reduced and how energy and cost savings can be done at the same time. The linear programming works on the entire microgrid and, according to the programme, tries to reduce the cost as well as carbon emissions. It works on the leader-follower rule or the community development algorithm. All the parameters that are calculated are defined as functions; the constraints are marked; and the power flow is defined. Once all the mathematical formulas are derived, the losses are also calculated with a formula. When the mathematical formulations are done, they are implemented into the model in the form of a linear programming algorithm that shows outputs related to cost and energy optimisation.

3) Non-Linear Programming: Non-linear programming is similar to linear programming, but the calculations are done considering non-linear equations. There is a recurring calculation that takes place until the constraints are fulfilled and a satisfactory solution is found. The variables keep changing with the number of iterations, and for that, gradient-based methods are used to work on objective functions that bring a change in the values of the variable function with each variable. With these complex computational problems like energy storage and hourly forecasts, accuracy in demand response can be achieved [16].

4) Meta-Heuristic Approach: It is applied to complex and dynamic structures. Additionally, it doesn’t rely on prior research, data, or mathematical models. They have large search spaces, discrete decision variables, and can have undefined functions too. They are used in the switching mechanisms of microgrids and grids, energy optimisation, cost analysis, and cost reduction. There are a greater number of iterations during the computation of this

algorithm; sometimes there are computation errors; the time limit for the result is not defined and can be uncertain; accuracy may increase or decrease depending on iterations, variables, functions, constraints, and other parameters in the model. But it gives an approximate result in the end, and that one can be taken as a reference for further computations to improve efficiency.

5) Other approaches to energy management systems in microgrids: There are various optimisation algorithm approaches that can be followed for energy management system optimisation in microgrids. The solutions can be accurate, moderately accurate, or approximate, considering different constraints, variables, functions, etc. The optimisation models can be followed by algorithms based on mathematical programming, artificial intelligence, neural networks, machine learning, heuristic approaches, meta-heuristic approaches, trajectory-based approaches, dynamic programming, and stochastic programming. [17]

The meta-heuristic approach along with the ant colony optimisation algorithm are highlighted in the model that focuses on load shifting and load shedding of critical and non-critical loads. When there is a grid failure or a power outage, the algorithm’s approach to renewable resources and energy storage systems is also highlighted. Starting from the next section to Section 5, the model has been described with an approach. The results, including energy savings, cost savings, and grid usage, have been presented.

3. Proposed model

3.1 Parameters in the model

The following parameters are taken as input along with their values: With these parameters, they are interconnected, and the ant colony optimisation algorithm is applied to receive the optimal solution. For all these parameters, a phasor of 60 Hz is taken as an input value during the entire simulation.

The source of the voltage is taken with a star-to-ground configuration. Considering the value as the voltage for the microgrid, the main grid power is taken as $250*10^6$ watts. The generator type taken is swing type or slack type. The domain here is the point of connection, and the variables taken are voltage (V), current (I), and power (P).

Equipment (Domain)	Values	Variables & Constraints
Three Phase step-down transformer	Variable Values (In Kilowatts)	Variables: V, I, P, R, L, F Constraints: Losses, resistance, inductance
Three-phase Switchgear/Breaker	phase-to-phase (Variable Values)	Variables: V, I, P, R, L, F Constraints: Interruption time of 0.01s and 0.04s
Line to Load Bus Link for Supply Cutoff (Distribution Side)	N/A	N/A
Line to Load Bus Link for Supply Cutoff (Load Side)	N/A	N/A
Variable Load (Load Fluctuation)	Assumed to be resistive load P=100KW-500KW	Variables: V, I, P, R, L, F Constraints: Timely load fluctuations
Fixed Load (Resistive)	Purely resistive load. PF=1 P=300KW	Variables: V, I, R, P, L, F Constraints: Over-consumption switches to variable load
PV Array	Values in Kilo Watts based on Solar Irradiance P=500KW	Variables: V, I, R, P, L, F Constraints: Irradiance profile as Clear Day and Cloudy Day
Wind Energy	Values in Kilo Watts based on Wind Generation. P=500KW	Variables: V, I, R, P, L, F Constraints: Low Wind/No Wind
Battery System (ESS)	Values based on Charging and Discharging between 0 to 100%, P=400KW	Variables: V, I, P, F Constraints: time of charging, discharging

Table 3 Parameters taken in the model as Domain, variables, and constraints

With the transformer, three single-phase transformers are taken into the simulation considering a smaller number of losses; the core and conductor values are not taken into calculation along with magnetization current (Imag), excitation currents (IRm), and fluxes. Capacitance is not considered because distribution of electricity to less than 50 kilometres is assumed. During the entire simulation, the load is assumed to be resistive. In addition to it, the windings taken are star-to-ground connected. The model is simulated considering the bidirectional power flow as it is carried on in the microgrid or the main grid.

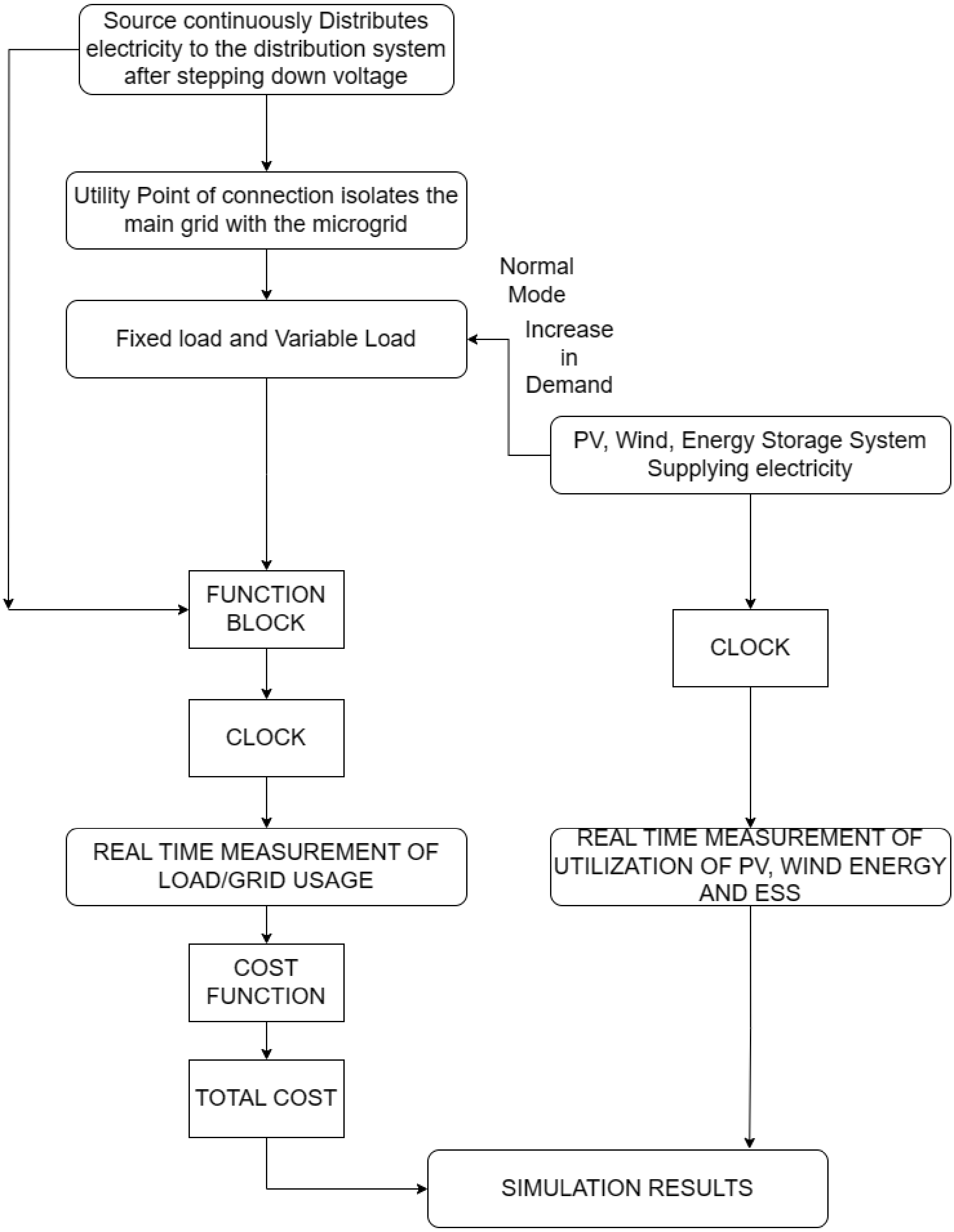

Figure 4 Flow of the Model and the application of logic

For the load fluctuation as per the time, different values are selected and stored as data. The values are taken for variable load in the model, as according to utilisation of power from the grid, load fluctuates on an hourly basis. The utility point of connections is connected with the microgrid and main grid. In the event of failure or an outage, the load gets isolated, preventing the microgrid from failing. On the other end, if demand for the main grid increases, the microgrid, through its renewable sources, can distribute electricity to the grid.

A random set of data for days and nights has been taken into the workspace for solar panels and an array. The parameter of weather is also taken as a constraint, such as a sunny day or a rainy day. During the entire simulation, the power factor has been considered 1 to prevent load lag or load leading. With the wind energy taken into consideration, the wind speed varies, and the other parameters are taken as random variables. As with the energy storage system or the batteries, 0%, or total discharge, is the low-low limit, and 100% is the high-high limit (fully charged).

The workings of this function block for fixed and variable loads include data collection for fixed and variable loads as well as electricity distribution done continuously. The function block is clocked, and the time frames are noted down. The real-time measurement is done for load, grid, PV source, wind source, and energy storage system. The cost function is pre-defined and is multiplied by the total source of electricity distribution done, from which we get our total final cost. The output characteristics and results are received from there.

A matrix of domains, variables, and constraints is formed for each piece of equipment where ant colony optimisation is implemented, which is discussed in the next section.

3.2 Ant Colony Optimization Framework- Discussing Variables, Constraints, Objectives

Ant colony optimisation is a meta-heuristic algorithm that was experimented with by Marco Dorigo in 1992 for solving the behaviour of ants and how the ants work together in a group. When ants travel, they drop a particle called a pheromone, and due to that, a colony of ants follows them. In the below node diagram example, there is a component of the solution on the path. The colony of ants keeps on following the nodes or that component of the solution by dropping a trace of pheromone. Ants try to find an optimal path by moving in a random direction with a certain motion. Each ant tries to find their local fit; when they reach a common node, they drop the pheromone and follow other components of the solution. That is when a final solution is achieved by targeting a global fit with the addition of multiple local fits.

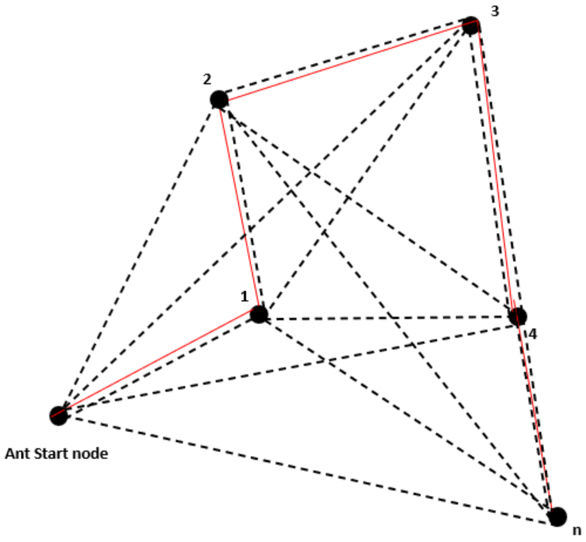

Figure 5 ACO Graph Construction for Nodes

For solving the optimisation problem, we define the variables, constraints, domains, etc. The graph is defined by three factors called a set of nodes, such as n_0, n_1, n_2, n_3, n_4, and n_n. After deciding the nodes or domains, the variables are defined where the path decisions can be made and potentially the ants can travel for a better solution. Then the constraints are discussed on where the ants cannot travel, the number of ants, the number of ants travelling together in a group, how many groups are considered, the time taken, and the distance to be travelled. To fulfil the criteria, there is a constraint satisfaction problem to be solved. So, from the constraints and variables, a solution comes up on each node, and a final solution comes up once the ants reach the final result. Ants always try to shorten their path, reduce their efforts, and solve their constraints. Hence, in the energy management problem, this can help reduce the cost of energy as well as make the problem more optimal. The final path that ants follow is represented in Figure 5 when the shortest path is discovered. For the ant colony optimisation to be derived, the following parameters are taken care of by the ants:

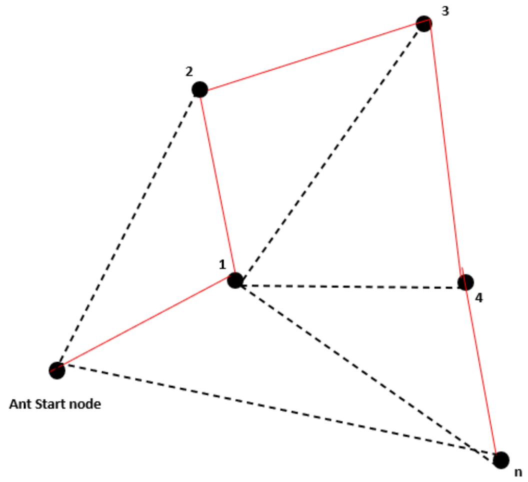

Figure 6 Optimal Solution Graph for Nodes

The parameters of the sources are defined: Each of the sources, the power supply through the grid, or the interconnection of the microgrid with the main grid is taken into consideration. The number of sources is defined as domains. For example:

Source 1 (the utility point of connection), transformer (step-down), circuit breaker, variable load, fixed load, PV array, wind array, and energy storage systems (ESS) are called domains. The generator or the source has all the parameters taken into consideration, such as voltage, frequency, power, current, power factor, load factor, phase-to-phase current, efficiency of the generator, losses, etc. Those are defined as variables. Constraints are discussed as the paths that cannot be followed or the limitations in the ratings.

- Pheromone particles and matrix are defined: The initial search by ants is done, and a limit is defined on how many ants are involved in the detection of a solution. The more ants, the more complex the problem, but the easier the solution and the faster it is. The matrix derivation also depends on the number of parameters.

- Local fitness: Each ant follows a path to find their solution and leaves a trace of pheromone. Each ant has a unique solution in the beginning and is uncertain how to reach its destination.
- Comparison of local fitness between ants: When each ant starts working on achieving their solution, the solution is compared based on the number of pheromones or the direction that has been followed.
- Global fitness: When initial iterations are completed and a common path is defined based on the number of pheromones, ants combine and follow their paths together to achieve a final solution.
- Matrix formation: with the final values, quantities are updated as the source's voltage, current, etc. And accordingly, all variables in all domains are defined. In such a way, the final matrix formation is done.

Now, when there is a change with the constraint or the decision variable, ants will detect the problem, as that was covered under a path, and will correct their solution and define a new optimal solution.

3.3 Algorithm Development for the model

There are k ants (k is a defined parameter) to move over a graph, and they have been given a command for the number of iterations (a limit for a solution) that they need to go through. The total number of ants will find certain groups and go forward on a path. Meanwhile, each of the ants will also try to find a local fit. As the ant succeeds, each local fit gets converted to a group local fit, and ants start placing pheromones for the other groups. The probability increases once all groups of ants keep finding local fitness and the local fitness level of each group is compared. Once again, ants start following the path until they find the global fit. Once global fit is achieved, pheromone levels start to drop, and the best fit (solution) is found.

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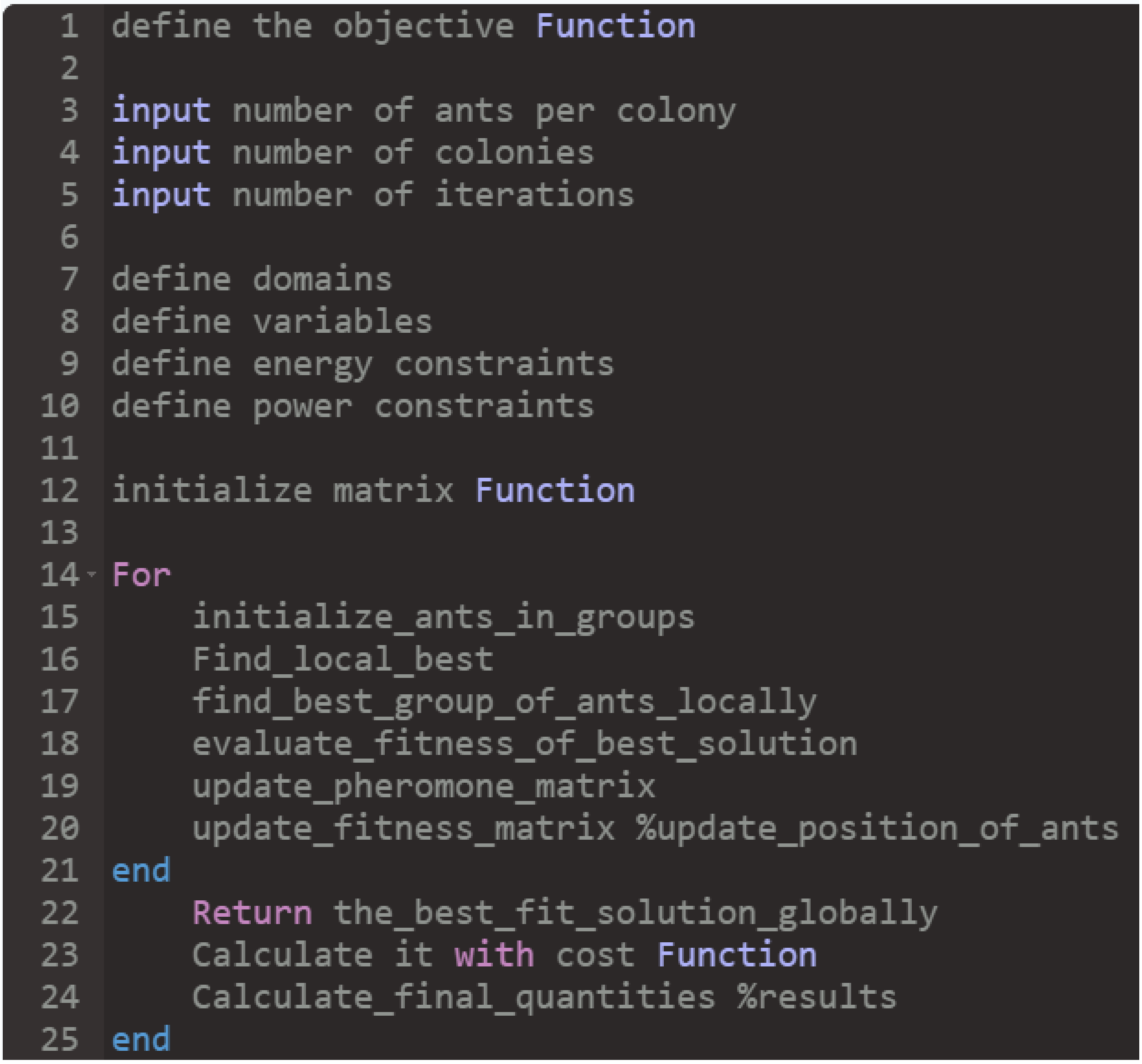

```
define the objective Function

input number of ants per colony
input number of colonies
input number of iterations

define domains
define variables
define energy constraints
define power constraints

initialize matrix Function

For
    initialize_ants_in_groups
    Find_local_best
    find_best_group_of_ants_locally
    evaluate_fitness_of_best_solution
    update_pheromone_matrix
    update_fitness_matrix %update_position_of_ants
end
    Return the_best_fit_solution_globally
    Calculate it with cost Function
    Calculate_final_quantities %results
end
```

Figure 7 ACO algorithm development for the EMS model for cost savings

The algorithm is implemented as code when parameters are taken and applied to a mathematical equation. When applied to the equation, different values are written as inputs in the matrix. The following parameters are defined for the formula where the algorithm is implemented, and then it starts forming its solutions based on domains, variables, and constraints in the energy management system. The parameters are as follows:

Description of Parameter	Parameter Denoted by
Probability of each ant (k) moving from Node a to Node b	P^{k}_{ab}
Trail or Path from node a to node b	P^{α}_{ab}
Pheromone level from node a to node b	η^{β}_{ab}
Trail or Path from node a to node c	P^{α}_{ac}
Pheromone level from node a to node c	η^{β}_{ac}

Parameter to reduce or limit the path length	α
Parameter to reduce or limit the quantity of pheromone	β
Boundary limit for ants to traverse for a solution	$\Sigma_{c\ \varepsilon\ (\text{allowed})_a}$

Table 4 Parameters for Probabilistic function

Probabilistic function function: $p^k_{ab} = (P^{\alpha}_{ab})\ (\eta^{\beta}_{ab})\ /\ \Sigma_{c\ \varepsilon\ (\text{allowed})_a}\ (P^{\alpha}_{ac})\ (\eta^{\beta}_{ac})$ …………… (1)

$P_{ab} = (1\text{-}p)\ P_{ab} + (\Sigma_k\, \Sigma_n)\ \Delta P^k_{ab}$ …………………………………………………………… (2)

$\Delta P^k_{ab} = Q/C_k$ or else 0 ………………………………………………………………… (3)

Pab is the amount of pheromone deposited by ants by traveling from node a to node b. p is the coefficient for the lifespan of pheromone, n is the number of ants, and $P_k$ab is the amount of pheromone deposited by kth ant. Q is a constant, and Ck is a cost function [18]

With the algorithm, we define domains, variables, and constraints. Then we define the number of ants per colony (per group), the number of colonies (groups), and the number of iterations (loops). The array of data is formed, and once the ants initialise their process, they start travelling to look for solutions. The probability of ants moving from one node to another is defined in equation 1, where each group has its own trail or path and emits pheromones. They have been defined by a certain boundary limit. When they emit a pheromone to find a local fit, there is a limitation to the lifespan of the pheromone. If the pheromone stays in one place for a longer time, then it can affect the processing time, and ants may take time to process a solution. Therefore, the lifespan of pheromones must be defined. When a matrix is formed, it is multiplied with a cost function to form the results.

Domains	Variables					
Source (S)	S_1V_1	S_1V_2	S_1V_3	S_1V_4	S_1V_5	S_1V_n
Transformer (T)	T_1V_1	T_1V_2	T_1V_3	T_1V_4	T_1V_5	T_1V_n
Breaker (B)	B_1V_1	B_1V_2	B_1V_3	B_1V_4	B_1V_5	B_1V_n
PV Array (P)	P_1V_1	P_1V_2	P_1V_3	P_1V_4	P_1V_5	P_1V_n
Fixed Load (F)	F_1V_1	F_1V_2	F_1V_3	F_1V_4	F_1V_5	F_1V_n
Variable Load (V)	V_1V_1	V_1V_2	V_1V_3	V_1V_4	V_1V_5	V_1V_n
Wind Energy (W)	W_1V_1	W_1V_2	W_1V_3	W_1V_4	W_1V_5	W_1V_n
ESS (E)	E_1V_1	E_1V_2	E_1V_3	E_1V_4	E_1V_5	E_1V_n

Table 5 Formation of domains and variables in Matrix form

When ants travel through different nodes and receive certain values as variables, we get values that are written as input in the form of a matrix. Once the entire matrix is formed, it is multiplied by the cost function. Ants pick up the best values from that matrix as a part of global fit. With the matrix formation by ants, we get overall grid usage, state of charge of batteries, voltage, power consumption, total cost, consumption by solar, consumption by wind, and consumption by grid.

The further discussion about collecting ratings hourly with grid usage, PV usage, wind usage, ESS SOC, integration with the cost function, and final results is highlighted in the next section.

4. Evaluation and findings

4.1 Implementation to the model

The algorithm is already defined, now to find the optimal solution, various alterations were done with the algorithm. The number of ants is changed. Less the number of ants, lesser the rate of efficiency was found, when ants were increased in numbers, the efficiency of model increased. Once, the number of ants were changed and altered, parameters such as voltage, power were altered in the model to find an optimal solution. The change in parameters also highlighted constraints with the design of transformer, PV array, Wind system, ESS, etc.

The power is distributed through the grid to the load, the variable load and fixed load when they keep changing, different cases are created. They are as follows:

1) On a sunny day if Power Distribution by grid > Power Consumption by variable load and fixed load. Energy distributed by grid, PV, Wind is stored in Energy storage system. Any additional power in the microgrid is distributed to the main grid.
2) On a cloudy day if Power Distribution by grid > Power Consumption by variable load and fixed load. Any additional energy distributed by microgrid; Wind is stored in Energy storage system. Any additional power is distributed to the main grid
3) On a sunny day if Power Distribution by grid = Power Consumption by variable load and fixed load. Energy distributed by PV, Wind is stored in Energy storage system
4) On a cloudy day if power distribution by grid = Power consumption by variable load and fixed load. Energy distributed by Wind is stored in Energy storage system or distributed to variable load in case of power efficiency
5) On a sunny day if Power distributed by grid < Power consumption by variable load and fixed load. Energy distributed by PV; Wind is distributed to the load. Power from ESS is also distributed to the load.
6) On a cloudy day if power distributed by grid < Power consumption by variable load and fixed load. Energy distributed by PV, Wind, ESS is distributed to the load. In case if the power demand is still more, additional power has to be supplied through other microgrids.

Once the concentration level, number of ants are changed and the parameters are changed. The idea is to setup the parameters with the Energy storage system. The central system here is Energy Management system based on Energy storage system. With a time, frame, the power consumption is divided into 24 discrete periods or time slots. The matrices formed, are divided into hourly basis. The cost of the grid is shown in two types. It is cost for cents/Kwh and total cost of the grid consumption in a day. The minimum operational cost of the grid or tariff is set to 14 cents /Kwh.

The parameters are formed as a global fit. The values are formed as Per minute/per hour/per day consumption. They are multiplied with cost. With this, we get the final power consumption of the microgrid in total grid usage as well as total cost for that grid usage. In addition to it, we also get to know the total consumption per Kilo Watt hours. With our findings, we also get to know the total consumption as well as characteristics during sunny day in normal mode, cloudy day in normal mode, sunny day in optimized mode and cloudy day in optimized mode

4.2 Results and discussion

The simulation runs, and with the results, the total grid usage keeps on increasing with discrete time frames. Grid usage continues to increase according to the consumption of electricity. The cost block is synchronised with grid usage to give the total cost.

Firstly, in normal mode, we run PV and a microgrid. The ESS system is kept stable. The power consumption solely depends on PV and the main grid, as shown in figure 8.

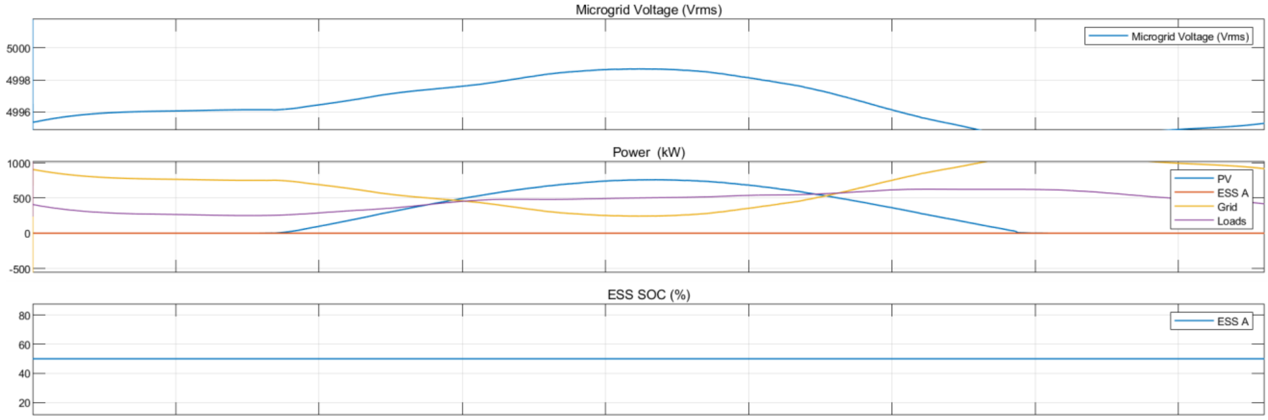

Figure 8: Characteristics in Normal Mode

When energy storage systems are also taken into account along with PV, then power demand is fulfilled by ESS and solar. When the demand is low, we observe that the ESS is charging, and then additional power is sent to the grid. Again, when demand rises, we observe that PV and ESS consumption go up, as mentioned in Figure 9.

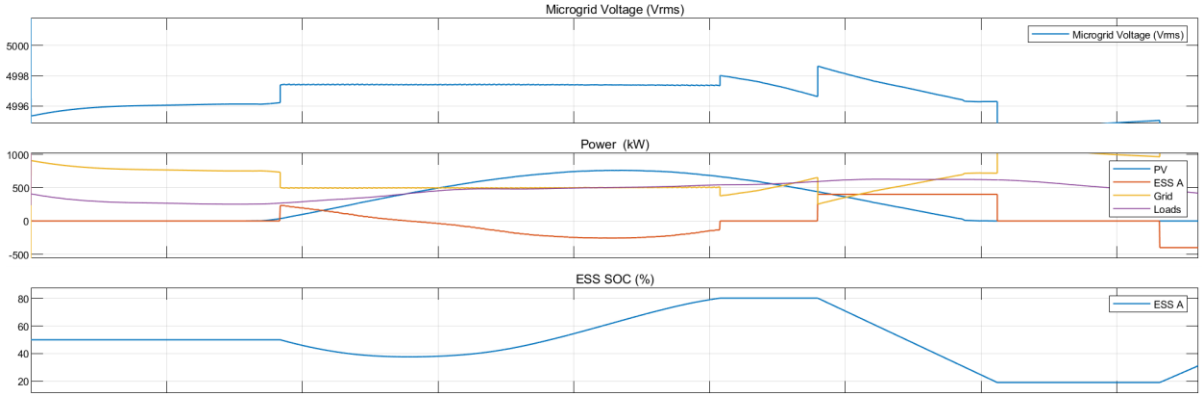

Figure 9: Characteristics on a Sunny Day in Normal mode

After a normal mode into PV, normal mode, and a sunny day, the simulation for a cloudy day in normal mode is taken into account, where wind is taken into account as the solar power gets dimmed down and ESS is kept stable. The voltage and power demand keep deviating on a cloudy day. In figure 10, we see that even though it is a cloudy day, no power is consumed from the grid. The entire power requirement is fulfilled by PV and wind systems. This tells us that microgrids can be reliable on renewable energy sources even without ESS in certain circumstances.

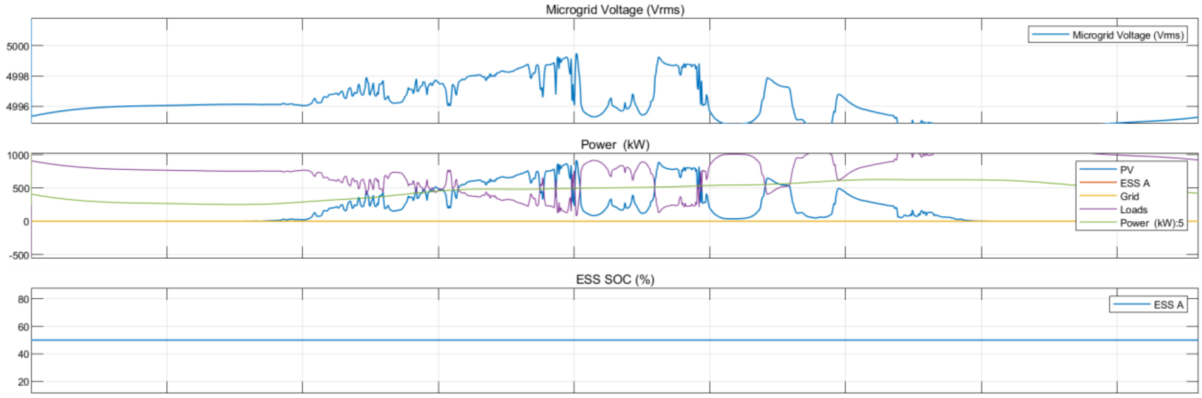

Figure 10: Characteristics on a Cloudy Day in Normal Mode

The simulations above were with an ant quantity of 50; now, with an ant quantity of 200, when we run into optimised mode on a cloudy day, we see that PV and ESS are both taken into account. When ESS SOC goes down, the main grid has to distribute power. But with a greater number of ants, we can observe that microgrid voltage or power consumption goes down in the end as it leads to more efficiency sooner.

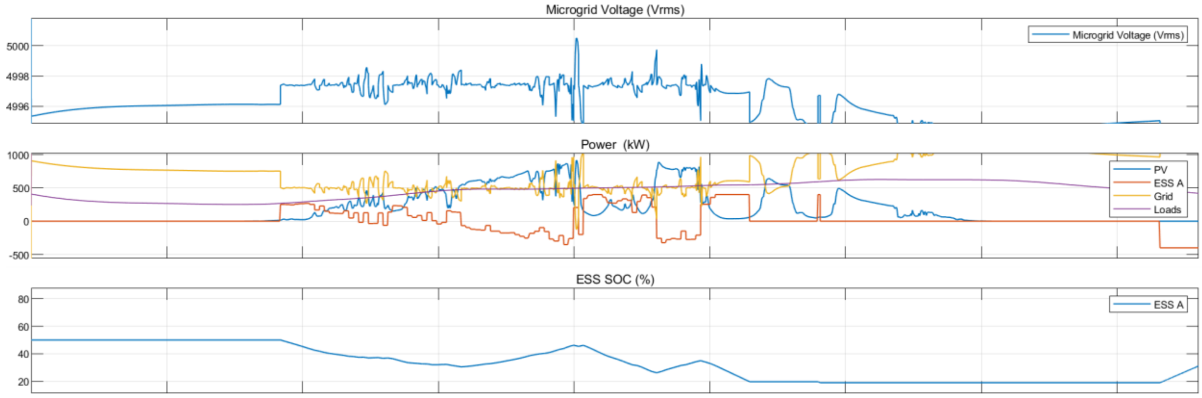

Figure 11: Characteristics on a Cloudy day in Optimized Mode with N=200

Now, as soon as we increase the number of ants to 500 in optimised mode, we observe that the efficiency increases. According to Figure 11, as power consumption or demand increases, the PV or wind system distributes power and also sends power to the grid. When the demand slows down, we can see that the grid power goes to neutral and ESS gets charged. At the end of the day, when the sun sets, we can observe that we do not take power from the grid; hence, the microgrid is solely dependent on wind power and ESS. This is when Ants gives the best efficiency and states that microgrid can run on ESS and wind systems when power from PV is not taken and when grid power is also not taken, instead grid transmits surplus power at the end of the day.

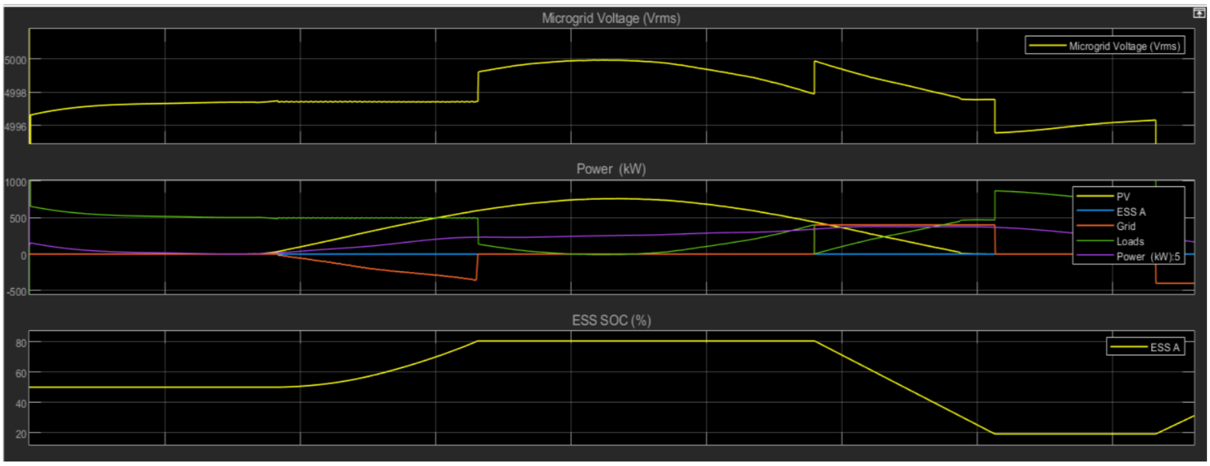

Figure 12: Characteristics on a Sunny Day in Optimized Mode with N=500

With similar types of power consumption, demand, and distribution, the pattern on a cloudy day is similar. The difference here is that the wind system stays stable and the PV system comes down at some point during the day. The PV system usually satisfies the load demand while the ESS SOC goes to peak.

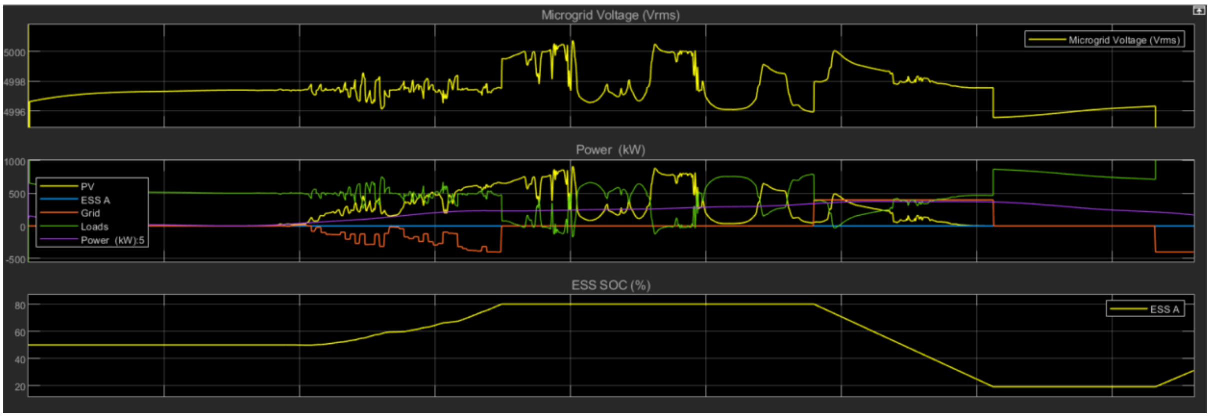

Figure 13: Characteristics on a Cloudy Day in Optimized Mode with N=500

With the cost of cents per kwh, the cost stays stable with 14 cents per kwh as the basic operational cost. The final cost of cents per kwh stays stable till the end, and then it reaches 28–30 cents per kwh. The cost is similar for all the simulations. When the total cost per usage is taken into account, it reduces when it is in optimised mode compared to heuristic mode or normal mode.

So, when power consumption increases, the microgrid can still rely on renewable energy sources instead of taking power from the main grid. With an increase in the number of ants, efficiency can increase and an optimal solution can be achieved. With all the simulations, the comparison between grid usage and total cost is also done. Additionally, we also keep cents per kwh even though the cost stays steady between 28 and 30 cents per kwh. In figure 16, the Y-axis is indicated with the cost, and the X-axis is the total power. Comparing Figure 16 with Figure 17, it is observed that even though the microgrid usage is higher in optimised mode, the cost is lower compared to normal mode.

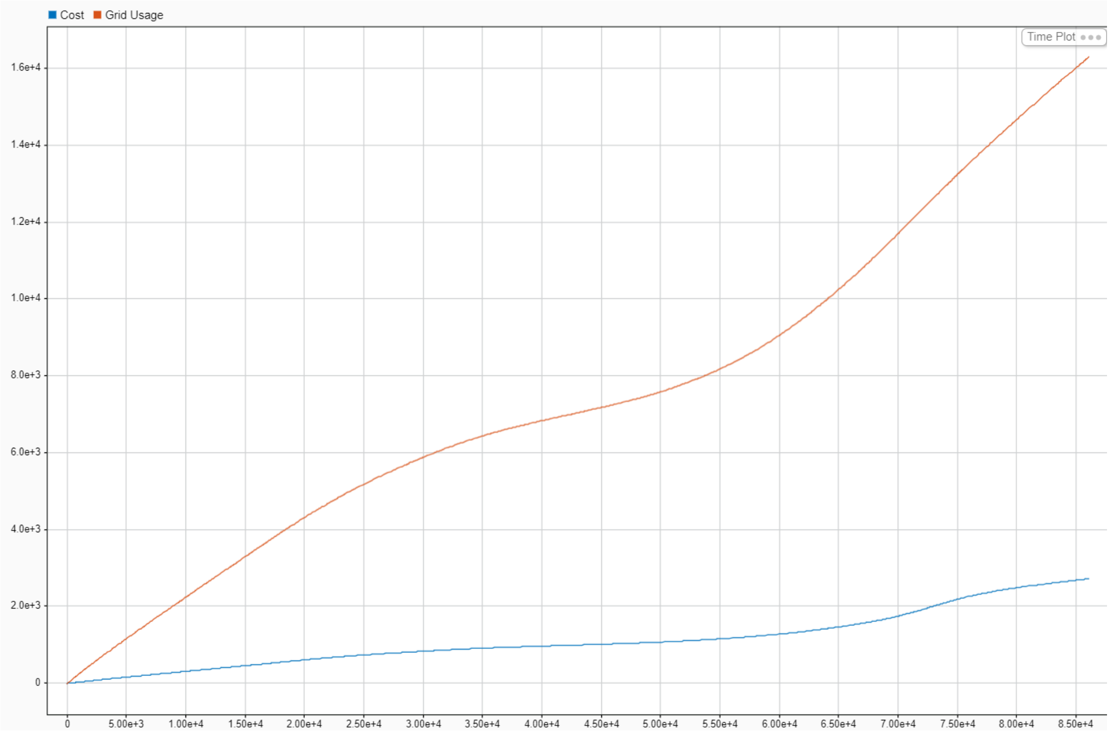

Figure 14: Grid usage vs Cost in Normal Mode

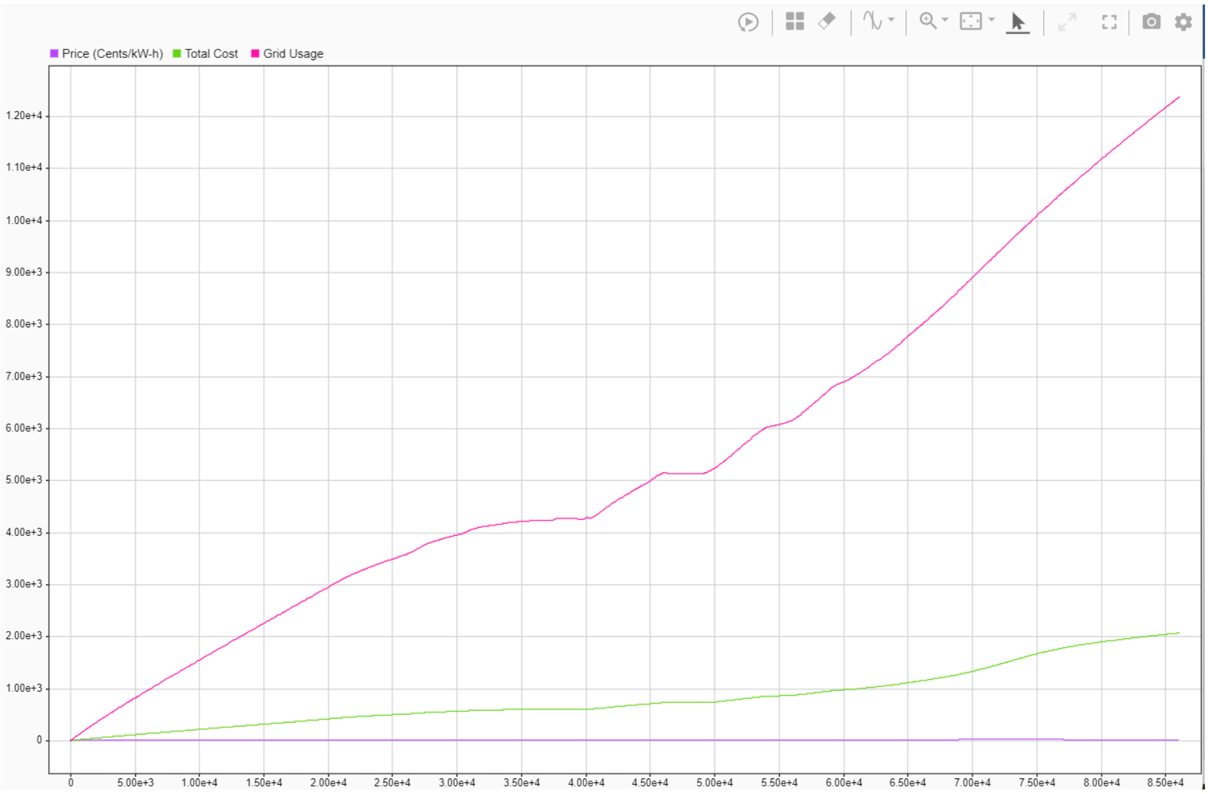

Figure 15: Grid Usage v/s Cost in Optimized Mode

As proven in figures 16 and 17, optimised mode is better compared to heuristic mode in the entire simulation. The total cost is way lower compared to heuristic mode. When the comparison between heuristic and optimised modes on a cloudy day is taken, as per the graph, the total cost on a cloudy day for heuristic mode is higher compared to optimised mode.

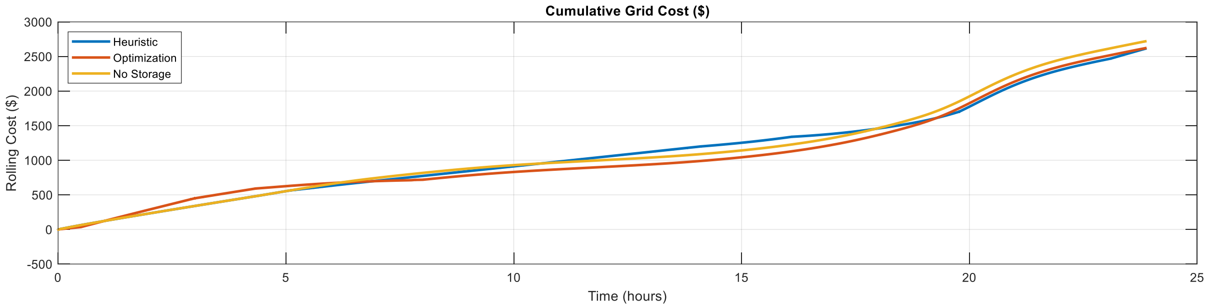

Figure 16: Cost in Heuristic v/s Optimization mode for Optimized simulation on a Cloudy day

Now, once all the simulations were done in heuristic mode for sunny days and cloudy days and optimised mode for sunny days and cloudy days, the results are written as follows in Table 6.

Mode of Optimization	Price/Cost of Utilization
Heuristic Mode on a Sunny/Normal Day	$2067
Optimized Mode on a Sunny/Normal Day	$1891
Heuristic Mode on a Cloudy day	$2655
Optimized Mode on a Cloudy Day	$2611

Table 6 Price/Cost of Utilization for Optimization Modes

According to Table 6, the cost of the grid in an optimised mode is $1891 compared to $2067 in a heuristic mode for power consumed for a day. These figures are taken with N = 500 as the number of ants. On a cloudy day, the cost in heuristic mode is $2655 compared to the cost in optimised mode, which is $2611. The cost received was much higher during cloudy days due to the inefficiency of energy storage systems and PV. Hence, the power was taken directly from the main grid.

The results depict that optimised mode with ant colony optimisation can bring a significant change, with a difference of $176 during a sunny or normal day and $44 during a cloudy day.

As per the objectives discussed earlier, we discussed about terms complexity, reliability, efficiency and performance. With implementation of ACO algorithm, we fulfil the objectives as follows:

Complexity: With normal mode, it was noticed that Microgrids are not able to take any decisions as they do not have control over EMS. With complexity, we mean about power distribution from the main grid to loads as well as microgrid to the loads With PV during a sunny day or cloudy day, the power distribution to load is imbalanced. With Normal mode, load shifting or load shedding does not happen. Load Shedding or load shifting happens through State of charge. When it comes to decision making, we see complexity with Normal mode. We overcome it by Optimized mode. According to Figure 12 and Figure 13, we see that whenever the microgrid has excess power, load shifting happens and whenever the load requirement is less, load shedding happens. This happens because of implementation of ACO. ACO decides the pathway or route to follow. Additionally, with more data and forming into discrete time frames, normal mode finds it complex and hence it can’t take any instant decisions. ACO implementation gives that decision power and hence reduces computational complexity.

Reliability & Efficiency: With the implementation of Ant Colony Optimization, reliability increases as the model has data collection, data processing, Ant behaviour simulation, local fit, global fit results, Path Selection, pheromone traces such that it can decide its own path. When we compare the results of Figure 10 and Figure 11, implementing ACO in optimized mode compared to normal mode gives us more optimal results. When we focus on increasing the accuracy and continuous improvement, we increase the number of ants to N=500 and Iterations=500 in Figure 12 and Figure 13, where we see that the microgrid distributes power to the main grid as the generation goes in excess because ants were able to achieve more optimal solution. This shows us we get optimal results. Hence, ACO focusing on continuous improvement increases efficiency with more ants and iterations and can be called as reliable as more ants and iterations do not affect the solution in a negative way. We focus on betterment through optimized algorithm and when we compare with Normal mode, we see optimized mode as more reliable.

Performance: Ant Colony Optimization algorithm is enhancing the performance of the microgrid with grid performance metrics. In grid performance metrics, it depends on voltage stability. While, in the normal mode the Energy management system does not operate, the model is not able to forecast the load, additionally there is no logic being implemented by the microgrid in terms of PV and State of charge of energy storage system. Hence, model does not know when to distribute power. ACO overcomes that constraint to distribute power as well as do a demand forecast. ACO optimizes the grid, the optimized mode shows more power distribution from Renewable energy sources compared to normal mode. According to Figure 15, we see that the optimized mode at $8*10^4$ W has more power being delivered at less cost compared to normal mode in Figure-14. When we compare both figures, we are evident that with power distribution comparison, optimized mode has better performance characteristics compared to normal mode. Additionally, considering the cost in optimized mode compared to normal mode at $8*10^4$ W, we get assured that we get relatively better performance with optimized mode compared to normal mode.

Hence, we can say that by implementing ACO, our complexity reduces, performance gets better, reliability and efficiency increases. Additionally, considering the economic criteria, the cost reduces compared to normal mode.

5. Conclusion & Future Scopes

The ant colony optimisation algorithm acts as a meta-heuristic method for the energy management system model. Energy savings and cost savings in the energy management system model can be achieved by the ant colony optimisation algorithm. With the microgrid, different domains, variables, and constraints are defined, and then a matrix is formed. With the algorithm, when the process is defined, the matrix keeps on getting its values. More the number of ants, the longer the processing time of the model, but the more efficient the model. With the simulation, the total usage of the grid, the cost of that usage, and the price in cents per kwh are calculated. The simulation is run in different modes, such as heuristic mode sunny day, heuristic mode cloudy day, optimised mode sunny day, and optimised mode cloudy day. Out of that, the optimal results are achieved in optimised mode on sunny days and optimised mode on cloudy days. The results show that with the implementation of the ant colony optimisation algorithm, optimal solutions are received with the microgrid, and a development of an energy management system can help the real grid solve the issue of grid demand, lower costs, and increase efficiency.

For future purposes, the approach would be to integrate machine learning and artificial intelligence. Once the model has trained itself, it can detect faults automatically. It can identify its own constraints and limitations and increase efficiency. Accordingly, the model itself can reduce energy costs. Future work also includes the integration of several microgrids and their formation into a smart grid. An implementation of a virtual power plant (VPP) can control the entire system of a microgrid. It can control the power factor automatically, voltage control, current control, and other variables. Another scope of work that can be implemented is cyber security into the system, as the system with all the sensors and equipment that are highly critical is highly vulnerable to cyber-attacks. Other algorithms can be applied in real time, case by case, with different applications. All the different algorithms can be applied to the same system in a single virtual power plant so that the control of the system can be taken care of and further optimisation can be done by the model itself. The automatic clearing of faults can be done in future work by developing various matrices. The scope of work is endless considering different applications in power systems and microgrids, but still, maintenance inspections will have to be done physically when it comes to troubleshooting the hardware.

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