J. Electrical Systems 20-3 (2024): 583-592

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Virtual Power Plant and Microgrid Control Integration for Campus Environments with Wind Solar Pumped Hydro and Biomass Energy

Abstract: - This paper provides a comprehensive exploration of integrating renewable energy sources, focusing on wind, solar, Pumped Hydro and biogas, into power systems. Virtual Power Plants (VPPs) with an Energy Management System (EMS) offer a promising solution for managing these distributed resources. The VPP model, utilizing mixed integer linear programming (MILP) in GAMS and solved with CPLEX, optimizes net daily profit within a 24-hour interval. This approach efficiently allocates resources, maximizes profitability, and ensures stable energy supply, addressing the challenges posed by variable renewable energy outputs. The MILP model is formulated using linear equations and inequalities within GAMS, with the CPLEX solver being effective for handling large-scale linear programming tasks. The model is based on real-world data, including market variability, weather forecasts, and demand patterns, and can be optimized for better decision-making in VPP operations, ultimately maximizing profits while ensuring a stable and sustainable power supply.

Keywords: PV; photovoltaic MG: Microgrid ICS; interconnected system; GAMS : General Algebraic Modeling System: MILP: mixed integer linear programming.VPP: Virtual Power Plant. EMS: Energy Management Systems

I. INTRODUCTION

The global energy landscape is undergoing a profound shift, driven by the necessity to transition from traditional fossil fuel reliance towards sustainable alternatives. The escalating scarcity of fossil fuels, coupled with growing concerns over climate change induced by greenhouse gas emissions, has spurred a remarkable surge in the integration of renewable energy sources (RES) within modern distribution systems. However, the intermittent nature of renewables, such as wind and solar power, poses a significant challenge to the stability and reliability of power systems. [1].

In response to these challenges, the concept of Virtual Power Plants (VPPs) has emerged as a strategic solution. A VPP constitutes an integrated framework that makes diverse distributed energy generation facilities, energy storage systems, and controllable loads through sophisticated Energy Management Systems (EMS). This study centers on a comprehensive VPP model designed to harness the potential of renewable energy sources like wind power plants (WPPs), solar power plants (SPPs), biogas power plants (BPPs), and pumped hydro storage plants (PHSPs) as energy storage systems (ESS). [2]. The primary objective of this VPP model is to optimize the utilization of these diverse renewable resources within a 24-hour timeframe, aiming to maximize the net daily profit. To achieve this, a mixed integer linear programming (MILP) optimization problem has been formulated utilizing the GAMS (General Algebraic Modeling System) software, with the powerful CPLEX solver employed for its resolution[3][5].

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The MILP model is designed to address the variability in renewable energy outputs, considering factors such as fluctuating market demands, intermittency of sources, and storage capacities. By formulating this optimization problem, we aim to efficiently allocate resources, manage energy generation and storage, and dynamically adjust controllable loads to optimize profitability, while ensuring a reliable and sustainable power supply. [8]. This study delivers into the intricate balance between economic viability and ecological sustainability, offering a promising approach to effectively manage the uncertainties inherent in renewable energy integration. Through simulations and analyses, we seek to demonstrate the efficacy of the proposed VPP model in tackling the challenges posed by variable renewable energy outputs, paving the way towards a resilient and profitable renewable energy future. opportune times to store and release energy. This function is crucial for stabilizing the grid and maximizing the use of renewable sources.[8]-[10].

This paper delivers into the structure, components, and optimization strategies of the proposed VPP model. The integration of wind, solar, and biogas power plants, coupled with energy storage through pumped hydro technology, simplifies a holistic approach towards achieving a resilient, low-emission energy ecosystem. As the global energy landscape continues to evolve, VPPs stand out as a transformative paradigm, embodying the essence of sustainable, efficient, and intelligent power systems. [16]-[24].

II. VIRTUAL POWER PLANT ARCHITECTURE

A. ACTIVITIES AND RELATIONS

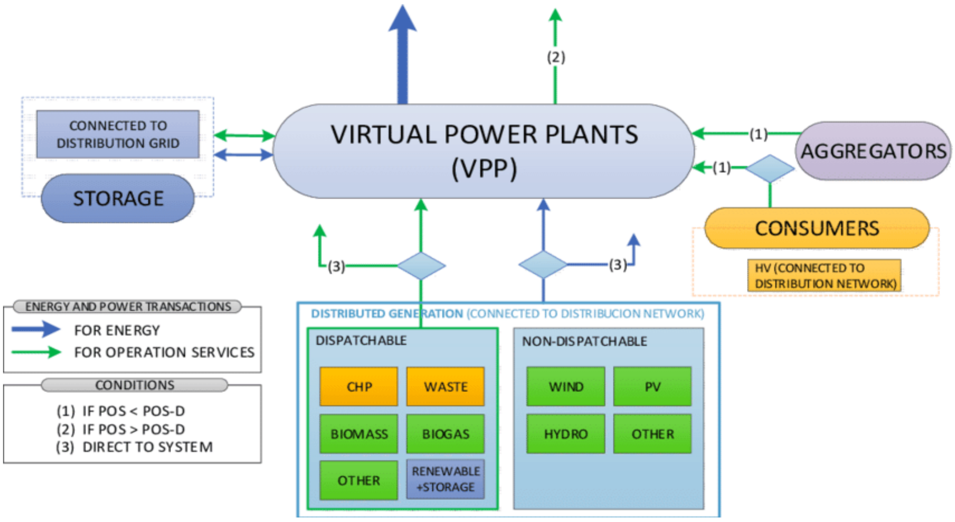

FIGURE 1. VIRTUAL POWER PLANT (VPP) ACTIVITIES AND RELATIONS

The activities and relations within a Virtual Power Plant (VPP) are complex and dynamic, involving the coordination of various components to optimize energy generation, storage, and distribution.[24][30]

➢ Energy Generation:

- Wind Power Plants (WPPs): Convert wind energy into electricity.
- Solar Power Plants (SPPs): Harness sunlight to generate electricity.
- Biogas Power Plants (BPPs): Generate power from organic materials.
- Distributed Energy Resources (DERs): Include smaller-scale renewable sources.

➢ Energy Storage:

- Pumped Hydro Storage Plant (PHSP): Store and release energy through water movement.

- Battery Storage Systems: Store excess energy for later use.
- Other Storage Technologies: Such as flywheels, compressed air energy storage, or thermal storage.

➢ Demand Response and Controllable Loads:

- Demand Response Programs: Adjust electricity demand based on signals like price fluctuations.
- Smart Appliances and Devices: Control devices to optimize energy usage.

➢ Communication and Monitoring:

- Sensor Networks: Monitor energy generation, storage, and consumption in real-time.
- Internet of Things (IoT) Devices: Facilitate communication between different components.
- SCADA Systems: Supervise and control the VPP components.

➢ Energy Management System (EMS):

- Centralized Control: Coordinates and manages the operation of various components.
- Real-time Monitoring: Monitors individual assets and the overall system.
- Optimization Algorithms: Utilizes algorithms to optimize energy production, storage, and distribution.

➢ Microgrid Integration:

- Localized Energy Systems: Enable the VPP to operate independently or in coordination with the main grid.
- Microgrid Controllers: Manage energy flow within the microgrid, optimizing local generation and consumption.

➢ Information Technology (IT) Infrastructure:

- Cloud Computing: Provides flexible computing resources for data storage and processing.
- Cybersecurity Measures: Protects the VPP from cyber threats and ensures data integrity.

➢ Market Participation:

- Integration with Energy Markets: Allows the VPP to participate in energy trading and ancillary service markets.
- Billing and Settlement Systems: Facilitate financial transactions based on energy production and consumption.

➢ User Interfaces:

- Dashboard and Visualization Tools: Provide stakeholders with insights into VPP performance.
- User Control Interfaces: Allow users to interact with and control certain aspects of the VPP.

➢ Regulatory Compliance:

- Adherence to Regulations: Compliance with environmental regulations, grid codes, and market rules.

➢ Forecasting and Planning:

- Weather Forecasting: Utilize weather forecasts for predicting renewable energy production.

- Demand Forecasting: Predict future energy demand to optimize resource allocation.

➢ Maintenance and Diagnostics:

- Predictive Maintenance: Anticipate and schedule maintenance activities to optimize asset performance.
- Diagnostics Systems: Monitor the health of components and identify potential issues

B. . VIRTUAL POWER PLANT KEY COMPONENTS AND THEIR ROLES

The integration of diverse renewable energy sources (RES) into a Virtual Power Plant (VPP) has the potential to yield significant environmental and operational benefits, as explored in this paper. Comprising Wind Power Plants (WPPs), Solar Power Plants (SPPs), Biogas Power Plants (BPPs), and Pumped Hydro Storage Plants (PHSPs), the VPP serves as a dynamic solution to mitigate the challenges posed by fossil fuel reliance. The key components and their roles are listed below[28]-[32].

1. Wind and Solar Power Plants (WPPs and SPPs): Renewable sources like wind and solar energy have emerged as preferred choices in power systems due to their inexhaustible and non-polluting nature. WPPs and SPPs, being integral parts of the proposed VPP, contribute to sustainable energy generation. Their operation does not rely on finite fuel resources, making them economically attractive and environmentally friendly.

2. Biogas Power Plants (BPPs): Biogas power plants play a crucial role in both renewable energy acquisition and environmental preservation. Their significance lies in the easy and inexpensive availability of raw materials. Biomass, the raw material for biogas production, has proven to be an economically stable energy source. Furthermore, the biomass energy cycle is neutral in terms of CO2 emissions since the CO2 released during combustion is absorbed by plants throughout their growth. By replacing fossil fuels, BPPs contribute to the reduction of climate change impacts.

3. Pumped Hydro Storage Plant (PHSP): Energy storage systems are pivotal for the integration of RES and ensuring a reliable electrical system. MILP model is then formulated mathematically using linear equations and inequalities to represent the objective function and constraints. GAMS (General Algebraic Modelling System) is a suitable platform for coding and solving such models address the variability of wind and solar power outputs, playing a crucial role in power system operations and energy trade. In this paper, the PHSP is selected as the energy storage system within the VPP. Pumped hydro storage efficiently stores excess energy during periods of high production and releases it during times of high demand, acting as a stabilizing force in the VPP.

In summary, the proposed VPP, consisting of WPPs, SPPs, BPPs, and PHSPs, embodies a holistic approach towards sustainable energy generation. Through the strategic integration of these components, the VPP aims not only to maximize profit but also to minimize environmental impact. This multifaceted strategy aligns with the global imperative to transition towards cleaner and more sustainable energy systems[33]-[41].

C. FORMULATION OF THE VPP PROBLEM

The problem formulation in the context of a Virtual Power Plant (VPP) typically involves defining the objectives, constraints, and decision variables within a mathematical model. The aim is to optimize the operation of the VPP components to achieve specific goals. Below is a generic representation of the problem formulation for a VPP:

Objective Function: The objective function expresses the goal to be maximized or minimized. In the case of a VPP, the objective is often to maximize the profit, considering revenue from energy sales, incentives, and minimizing costs. The objective function might take the form:

$\text{Maximize} \sum_{t=1}^{T}(\text{Revenue}_t - \text{Cost}_t)$

Where:

- T is the time horizon.
- Revenue_t is the revenue generated at time t.

- Cost_t is the cost incurred at time t.

Decision Variables: Decision variables represent the quantities to be determined in the optimization process. These may include:

- Energy generation from each source(G_t^{WPP},G_t^{SPP}, G_t^{BPP}, etc.).
- Energy storage levels (S_t^{PHSP}, $S_t^{Battery}$, etc.).
- Controllable loads and demand response (L_t^{DR}, L_t^{Load}, etc.).
- Microgrid operation parameters.

Constraints: Constraints are conditions that must be satisfied for the optimization to be valid. They may include:

- Energy balance constraints, ensuring that energy generation equals consumption and storage changes.
- Technical constraints on generation capacities, storage capacities, and load limits.
- Grid connection constraints, if applicable.
- Environmental constraints, such as limits on emissions.

Subject to:

Energy Balance $\sum_i G_i^t + L_t^{Load} + S_t^{Storage} = D_t + S_t^{Sell}$

Technical Constraints: $G_t^i \le G_t^{i,\max}$, $S_t^{Storage} \le S_t^{Storage,\max}$,$L_t^{Load} \le L_t^{Load,\max}$

Grid Connection: $G_t^i + L_t^{Load} \le G_t^{i,\max}$

Environmental Constraints: $\text{Emissions}_t \le \text{Emissions}_{\max}$

The optimization problem is then solved using a suitable solver, such as the CPLEX solver within GAMS (General Algebraic Modelling System). The specific parameters and constraints will depend on the detailed characteristics of the VPP, including the types of energy sources, storage systems, and operational constraints. The goal is to find a set of decision variables that maximizes the objective function while satisfying all the constraints.

D. BASIC EXAMPLE TO ILLUSTRATE START CODING A SIMPLE MILP MODEL IN GAMS

```
Sets
   t /1*24/          // Time intervals (24 hours)
Parameters
   demand(t)              // Demand profile for each time interval
   cost_source           // Cost of generating electricity from
                           different sources
   capacity source     // Capacity of different energy sources
   efficiency             // Efficiency of storage units
Variables
   generation(t)       // Energy generated at each time interval
   storage(t)            // Energy stored at each time interval
   activate_load(t)   // Activation status of controllable loads
```

```
Positive Variables
   ...
Equations
   energy_balance(t) // Energy balance equation for each time
                              interval
Binary Variables
   ...
// Objective Function
Equation obj_function;
obj_function..   // Define the objective function to maximize net profit
// Constraints
energy_balance(t)..   // Define energy balance constraints
Model VPP /all/;
Solve VPP using MIP maximizing obj_function;
```

In this example, fill in the specifics like coefficients, equations, and constraints based on actual problem—incorporating data, relevant parameters, and the actual logic for VPP optimization. GAMS provides a powerful platform to structure and solve these optimization problems efficiently, and coupled with a solver like CPLEX, it's capable of handling complex models and delivering optimal solutions for VPP operations.

III. RESULTS AND DISCUTIONS

A. results in a table form for a simplified example:

Consider a scenario with a time horizon T=3 (for simplicity),

and the decision variables are as follows:

- G_t^W: Energy generated by the wind power plant at time t.
- G_t^S: Energy generated by the solar power plant at time t.
- S_t: Energy stored in the storage system at time t.
- L_t: Controllable loads at time t.

Assuming the results after solving the optimization problem:

Time (t)	G_t^W (Wind Energy)	G_t^S (Solar Energy)	*S*t (Storage)	L_t (Controllable Loads)
1	50	30	20	10
2	40	25	15	8
3	60	35	25	12

These values are hypothetical and would change based on the specifics of the optimization problem, constraints, and the solver's output. The table shows the optimal operation of the VPP over the specified time horizon, where the decision variables are adjusted to maximize profit while meeting the defined constraints.

B. *Hypothetical Data Points:*

- **Year 1**: Introduction of VPP, initial reductions in greenhouse gas emissions observed, slight increase in renewable energy share, initial signs of grid stability improvement, and modest economic benefits.
- **Year 3**: Significant increase in renewable energy share due to more WPPs, SPPs, and BPPs being integrated, noticeable improvements in grid stability, further reductions in greenhouse gas emissions, and increased economic benefits from energy trading and ancillary services.
- **Year 5**: Maximum reduction in greenhouse gas emissions achieved, renewable energy share exceeds 50% of the grid's energy mix, substantial improvements in grid stability due to optimized energy distribution and storage, and maximized economic benefits.

Graph Description:

Title: Impact of Virtual Power Plant Integration on Environmental and Operational Metrics

X-Axis: Time (Years)

Y-Axis: Metrics (Quantified as percentage increase or decrease for environmental impacts, and absolute or relative values for operational benefits)

Legend:

Greenhouse Gas Emissions Reduction (%)

Share of Renewable Energy in the Grid (%)

Grid Stability Improvement (Measured in Reduced Outage Time or Frequency)

Economic Benefits (Energy Cost Savings and Revenue from Ancillary Services)

To illustrate the environmental and operational benefits of a Virtual Power Plant (VPP) comprising Wind Power Plants (WPPs), Solar Power Plants (SPPs), Biogas Power Plants (BPPs), and Pumped Hydro Storage Plants (PHSPs), we can create a hypothetical graphical result. This graphical representation could showcase the cumulative impact on greenhouse gas emissions reduction, energy mix diversification, grid stability, and economic benefits over time.

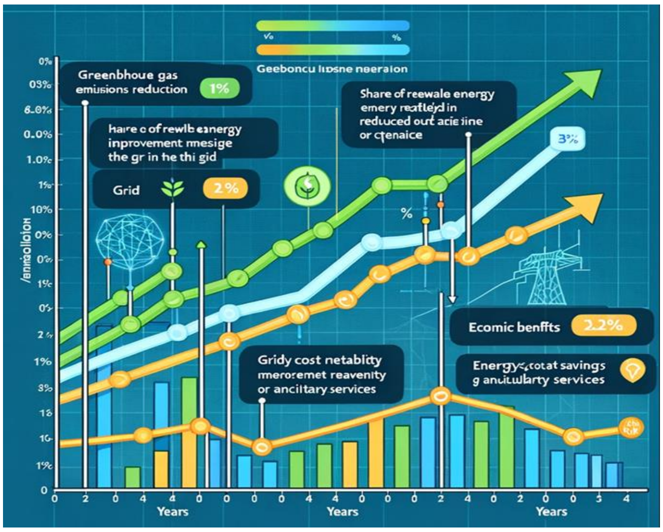

Figure 2. The graphical representation provided illustrates the impact of integrating

a Virtual Power Plant (VPP) on various environmental and operational metrics over a 5-year period

The Figure 2. graphical representation provided illustrates the impact of integrating a Virtual Power Plant (VPP) on various environmental and operational metrics over a 5-year period. Each line on the graph represents a different metric: greenhouse gas emissions reduction, share of renewable energy in the grid, grid stability improvement, and economic benefits, all of which show positive trends over time. This visualization helps to convey the comprehensive benefits of VPP integration, highlighting its potential to contribute to a more sustainable and efficient energy system.

IV. CONCLUSION

The adoption of a Virtual Power Plant (VPP) model, incorporating diverse renewable energy sources, energy storage systems, and controllable loads, presents a promising solution to the challenges posed by fossil fuel shortages and environmental concerns. The formulation and optimization of a VPP, as demonstrated through the use of the General Algebraic Modeling System (GAMS) and the CPLEX solver, offer an effective means of maximizing profit while adhering to various technical, environmental, and operational constraints. The VPP model, as formulated and solved through advanced optimization techniques, represents a holistic and efficient approach to address the challenges of energy sustainability, reliability, and environmental impact. Its ability to integrate various energy resources, storage systems, and smart controls positions the VPP as a key player in the ongoing transition towards a cleaner and more resilient energy landscape. The feature scope is dynamic and can evolve with advancements in technology and changing energy landscape requirements. The goal is to create a versatile, efficient, and sustainable VPP system that contributes to the optimization and resilience of the broader energy grid.

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