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Proposed Architecture of the Virtual Power Plants for the South African Power Grid

Melissa-Jade Williams [a*], Chang Choong-koo [a]
[a]*Nuclear Power Plant Engineering Program, KEPCO International Nuclear Graduate School, 658-91 Haemajiro, Seosaeng-myeon, Ulju-gun, Ulsan, 45014*
[*]*Corresponding author: WilliaM@eskom.co.za*

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1. Introduction

South Africa's is currently experiencing electricity insecurity. To address this, initiatives, such as the Integrated Resource Plan 2019 (IRP 2019), to increase the generation capacity and diversify the energy mix to include more renewable energy sources, have been implemented. The seamless integration of Virtual Power Plants (VPPs) with the existing national grid in South Africa is a critical undertaking to realize the ambitious targets outlined in the IRP 2019. This paper will delve into the optimal strategies and key considerations for VPP integration to providing an innovative solution to address the intermittency challenges posed by renewable energy sources.

Optimizing VPP integration requires a robust assessment of grid compatibility and stability. Studies, such as the work of Sivakumar et al. [1], highlight the significance of grid modelling and simulation techniques to evaluate the impact of VPPs on grid operations. Advanced power system simulation tools can assess voltage stability, transient stability, and frequency control under various VPP penetration scenarios. Furthermore, Wang et al. [2] emphasize the use of advanced control algorithms, such as model predictive control, to maintain grid stability while efficiently coordinating Distributed Energy Resources (DERs) within the VPP.

Effective communication and control mechanisms are critical for VPP integration. In their study, Li et al. [3] propose a hierarchical control structure for VPPs that encompasses centralized control, local control, and peer-to-peer communication. This architecture ensures real-time coordination and decision-making among DERs, enabling optimal power dispatch and grid response. Leveraging secure communication protocols, as suggested by Zanni et al. [4], helps safeguard VPP operations against cyber threats and enhances overall system reliability.

Ultimately, the best option for a VPP in South Africa would be a well-planned and comprehensive approach that considers the unique characteristics of the region, optimizes the utilization of available resources, addresses technical and regulatory challenges, and aligns with the country's energy goals outlined in the IRP 2019.

As there are currently no VPPs in South Africa, the goal of this research is to ascertain the optimal VPP architecture for South African power grid integration.

The remainder of the paper is structured as follows. Section 2 reviews the current literature and examines the challenges to overcome and factors to consider to successfully integrate VPP's into the South African grid. The analysis and results regarding energy management systems are discussed in section 3. The paper is concluded in section 4.

2. Methods and Results

By aggregating and intelligently managing diverse renewable energy resources, VPPs offer an opportunity to achieve sustainable energy goals, enhance grid stability, and promote equitable energy access. However, overcoming the regulatory, technological, and market-related challenges requires collaborative efforts from policymakers, energy stakeholders, and research communities.

Research by Samarakoon et al. [5] underscores the significance of accurate renewable energy forecasting, such as solar irradiance and wind speed prediction, for VPP planning and operational strategies. Furthermore, Sajjad et al. [6] proposes hybrid VPP configurations that combine various RES technologies, such as solar PV and wind turbines, to ensure a balanced and reliable energy supply. Effective utilization of these resources in a VPP framework requires sophisticated forecasting models, monitoring and optimal dispatch algorithms, and coordination mechanisms to ensure reliable and predictable energy delivery [7, 8].

2.1 Technical Requirements for VPP

2.1.1 Regulatory Framework and Market Structures

Rezaeibagha et al. [9] highlights the significance of a supportive regulatory framework and appropriate market structures to incentivize VPP integration. Well-designed feed-in tariff mechanisms, energy trading platforms, and demand response programs encourage VPP operators and DER owners to participate actively in grid services, ensuring a smooth transition towards a more decentralized energy ecosystem. VPP's intelligently integrate distributed energy resources (DERs) and co-ordinate their collective operations. These DERs encompass a diverse array of technologies, including but not limited to solar photovoltaic (PV) systems, wind turbines, energy storage systems (ESS), demand-side management (DSM) technologies, and electric vehicles (EVs).

2.1.2 Control and Communication Technology

Demand-side management (DSM) techniques are vital components of VPPs as they enable demand response capabilities, enhancing grid flexibility and load balancing. Integrating smart grid technologies, such as smart meters and home energy management systems, empowers consumers to actively participate in energy conservation and load-shifting practices, thus optimizing VPP performance [7, 8]. Furthermore, a study [10] focuses on the technical and economic aspects and limitations of the scheduling problem associated with VPPs, suggesting the use of Deep reinforcement learning (DRL) to address these challenges.

2.1.3 Energy Access and Decentralization

VPPs present an opportunity to extend electricity access to remote and underserved regions in South Africa. By deploying small-scale renewable energy systems and microgrids, VPPs can enable energy independence and local economic development, aligning with the country's commitment to energy decentralization [7, 8].

2.2 VPP Energy Management System Best Suited to South African Grid based on Previous Studies

2.2.1 VPP Architecture

There are two types of architecture mentioned in [11]. The first type of architecture is the Centralized Operational Architecture. In this architecture, the aggregator coordinates its operation directly with the system operator and offers the available resources from a set of DERs. In this architecture, the VPP actively participates in the markets in a similar way to a conventional power plant. The second type of architecture is the Decentralized Operational Architecture. In this architecture, the aggregator coordinates its operation and offers its services to the DSO. In this architecture, the DSO could actively participate in markets with supply/demand for services with the system operator. Proposed architectures are analysed for coordination and emphasizes the importance of appropriate coordination mechanisms to meet technical and commercial requirements in the electricity markets.

2.2.2 Classification of VPP

VPPs, orchestrated by the Internet of Energy (IoE), are flexible organizations categorized into two primary classes: Commercial VPPs (CVPPs) and Technical VPPs (TVPPs). CVPPs emphasize economic optimization, including electricity market participation and profit maximization. TVPPs focus on ensuring the technical performance of power systems, prioritizing safe, reliable, controllable, and secure operations and real-time monitoring of Renewable Energy Sources (RESs). TVPPs furnish data to network regulators, specifically the Independent System Operator (ISO), for pricing, while CVPPs contribute economic and financial reports.

2.2.3 Energy Management System

Energy management depends heavily on the scheduling algorithm in virtual power plants (VPPs), which takes into account many technical, financial, and unpredictable factors that can have an impact on the scheduling program. Through the use of accurate forecasting and scheduling algorithms, VPPs may enhance energy management while boosting power system stability and dependability. Furthermore, because the scheduling algorithm maximizes prosumers' excess energy, prosumers that install any kind of small-scale RESs or storages can trade in the market through VPPs. The Energy Management System (EMS) serves as the core of VPP operations. Sub-EMS units within the VPP communicate bidirectionally with the central EMS, relaying information on the aggregated energy resources, generation capacity, and energy consumption. The central EMS, through data analysis, optimizes VPP performance, while sub-EMS units oversee component behavior and may be configured to balance costs and user preferences. The EMS relies on precise data from power generators to consumption points and requires resilient communication networks and scalability, even under network failures.

3. Proposed Architecture for VPPs in South Africa

General architecture for the management of net zero or nearly zero energy grids is optimal. The architecture shall be based on the concept of a bottom-up operation, where the VPPs are the fundamental basis for the technical and commercial operation of DERs. The VPPs shall be responsible for managing the offers from each DER and making them available to the system operator by acting as the integrating agent. In this way, supply and demand services will be coordinated in the electricity market. Coordination between operators (TSO and DSO) and participants of the electricity production system (EPS) shall be evaluated for their effectiveness in market participation. The coordination strategies, aggregators will not only participate in ancillary service markets, but they could also coordinate their operation with the TSO and DSO to participate in the traditional energy and reserve markets. Optimal scheduling shall improve reliability and stability in the power system due to better energy management in both users and provider sides and thus decrease generation, transmission, and maintenance costs.

[19] discusses various ways in which VPPs can interact with different types of electricity markets, including day-ahead, intraday, balancing, and reserve markets. These interactions can be optimized using different techniques, such as stochastic programming, mixed-integer programming, and game theory. Additionally, VPPs can participate in demand response programs and provide ancillary services to the grid.

The proposed VPP frequency control strategy in [12] uses two types of controllers: the proportional integrator derivative (PID) controller and the two-stage (PI)-(1+PD) controller. The two-stage controller is a combination of a proportional-integral (PI) controller and a proportional-derivative (PD) controller. The PI controller is used to regulate the steady-state error of the system, while the PD controller is used to improve the transient response of the system. The gains of these controllers are optimized using various optimization tools such as PSO, FA, BOA, and GOA. The objective function to be minimized is an integral squared error (ISE) of the frequency deviation of the VPP model and the tie-line power. Based on VPP modelling using MATLAB, the two-stage controller shall be used since it successfully maintains stable dynamic VPP operation. In addition, the GOA algorithm shall be employed since it performs better when compared to the other optimization tools.

4. Conclusions

VPPs can manage the distributed elements through the Distributed Energy Resource Management System (DERMS), but the efficient use of available resources depends on optimal coordination with the system operator (the TSO), or with the local operator (the DSO) [11].

A two-stage optimization strategy for virtual power plants (VPPs) that incorporates demand response and energy complementation has been found to be optimal. Challenges associated with integrating VPPs into a country's existing infrastructure, such as the uncertainty of wind power, photovoltaics, and load, and the increase in computation time with the extension of the scheduling period. The first stage of the proposed strategy is a day-ahead scheduling that uses a scenario-based approach to form a preliminary dispatch plan. The second stage is a real-time scheduling that corrects the day-ahead scheme through rolling optimization on a reduced time scale. The authors also introduce an improved DR program that takes into account both the compensation and penalty mechanism in the form of a bilateral contract between VPP and energy users for a reasonable response [13]. Thus, even though the centralized architecture seems simpler to implement, the optimal architecture to employ and satisfy the needs of South Africa is the decentralized operational architecture.

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