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Dynamic Power Hierarchies: Controlling Isolated Micro-grids with Precision

***Abstract**. The management of isolated microgrids is a complex and challenging task due to their dynamic nature and evolving control systems. To address these challenges, a novel hierarchical control scheme is proposed in this article that operates across daily, weekly, and monthly horizons. The proposed scheme aims to enhance the stability and security of the power system, facilitate the integration of renewable energies, and reduce reliance on expensive and polluting diesel generators. Implemented using Matlab/Simulink, the proposed control scheme uses a multi-level loop concept to provide optimal operation of the isolated network. The primary, secondary, and tertiary control levels provide essential functions for an AC micro-grid, enabling the connection of different sources of alternating current, particularly renewable energy sources. The scheme has demonstrated its effectiveness in achieving optimal load sharing, voltage and frequency regulation, and reactive power sharing in isolated microgrids. The introduced decentralized control strategy modifies the static control parameters based on corresponding local information, improving the accuracy of frequency restoration and reactive power sharing in isolated microgrids. The results of simulations have significant implications for the efficient management and utilization of isolated networks, particularly in the context of renewable energy integration. Overall, this study contributes to the advancement of microgrid control technology and opens up new avenues for future research to improve the performance and reliability of microgrid systems.*

***Streszczenie.** Zarządzanie izolowanymi mikrosieciami jest złożonym i wymagającym zadaniem ze względu na ich dynamiczny charakter i ewoluujące systemy sterowania. Aby sprostać tym wyzwaniom, w tym artykule zaproponowano nowy hierarchiczny schemat kontroli, który działa w horyzoncie dziennym, tygodniowym i miesięcznym. Proponowany program ma na celu zwiększenie stabilności i bezpieczeństwa systemu elektroenergetycznego, ułatwienie integracji energii odnawialnej oraz zmniejszenie uzależnienia od drogich i zanieczyszczających środowisko generatorów diesla. Zaimplementowany przy użyciu Matlab/Simulink, proponowany schemat sterowania wykorzystuje koncepcję wielopoziomowej pętli w celu zapewnienia optymalnej pracy izolowanej sieci. Podstawowe, drugorzędne i trzeciorzędne poziomy sterowania zapewniają podstawowe funkcje mikrosieci prądu przemiennego, umożliwiając podłączenie różnych źródeł prądu przemiennego, w szczególności odnawialnych źródeł energii. Schemat wykazał swoją skuteczność w osiąganiu optymalnego podziału obciążenia, regulacji napięcia i częstotliwości oraz podziału mocy biernej w izolowanych mikrosieciach. Wprowadzona zdecentralizowana strategia sterowania modyfikuje parametry sterowania statycznego w oparciu o odpowiednie informacje lokalne, poprawiając dokładność przywracania częstotliwości i podziału mocy biernej w izolowanych mikrosieciach. Wyniki symulacji mają istotne implikacje dla efektywnego zarządzania i wykorzystania odizolowanych sieci, szczególnie w kontekście integracji energii odnawialnej. Ogólnie rzecz biorąc, badanie to przyczynia się do rozwoju technologii sterowania mikrosieciami i otwiera nowe możliwości dla przyszłych badań nad poprawą wydajności i niezawodności systemów mikrosieci. (**Hierarchie mocy dynamicznej: precyzyjne sterowanie izolowanymi mikrosieciami**)*

Keywords: Distributed generators,Droop control,Hierarchical control,Microgrid.
Słowa kluczowe: Generatory rozproszone, sterowanie Droop, sterowanie hierarchiczne, mikrosieć.

1. Introduction

Electricity can be produced reliably and securely through decentralized generation at a lower cost. The use of combustion generators, known as "distributed generation (DG)," was reliable but environmentally unfriendly. Renewable energy systems like solar photovoltaic, wind, biomass, etc., have gained popularity as options for distributed generation [1].

Distributed generation (DG) offers three categories of benefits: technical, economic, and environmental. From a technical perspective, DG supports power supply to remote communities, enhances energy efficiency, mitigates grid vulnerability, and reduces blackouts. Economically, DG reduces emissions, line losses, customer interruption costs, fuel expenses, and ancillary service expenses [2, 3]. Environmental benefits include reduced emissions, a smaller production footprint, increased clean energy sources, and decreased dependence on external fuel [4].

While renewable energy sources are clean and sustainable, they face challenges such as power discontinuity due to the intermittent nature of solar and wind energy. A hybrid approach that combines renewables with traditional power generation methods is needed to ensure a consistent electricity supply [5, 6]. This hybridization provides a backup power source when renewables cannot meet demand, resulting in a more reliable and stable energy supply [7].

Distributed generators (DGs) cannot directly connect to the AC bus. Therefore, power electronic interfaces are essential for integrating DGs into the power system, enabling control, protection, and efficient conversion of DC power to AC power [8]. Unique control mechanisms are required to transition between grid-connected and stand-alone systems. A hierarchical, multi-layered control technique ensures reliable operation by addressing frequency, voltage, and power sharing requirements [1, 9].

The primary layer of the control approach regulates power parameters (voltage, current, and power), while the secondary layer corrects errors and compensates deviations during steady-state operation. A multi-layered control strategy contributes to the stable operation of stand-alone and grid-connected systems, simplifying power system administration [8, 10, 11].

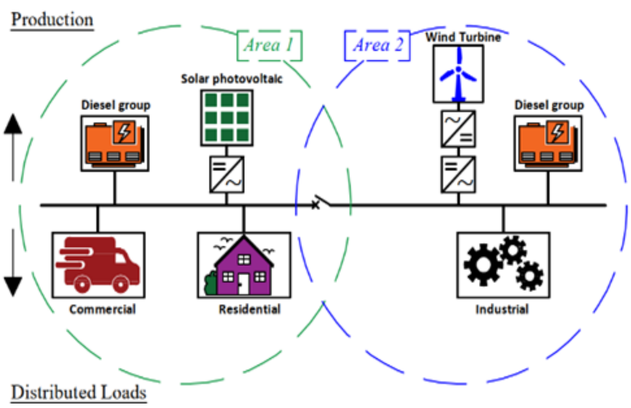

Fig.1: A typical design of an isolated micro-grid powered by a renewable energy source

Figure 1 illustrates the architecture of an isolated network with a radial topology and multiple connection points for residential, commercial, and industrial loads [12–14]. Different load demands are accommodated, and power is efficiently distributed across the network [15, 16].

The micro-grid is composed of two significant areas, each serving a distinct purpose. The first area encompasses a diesel generator serving as the primary source of electricity, a photovoltaic park, and a mixture of residential and commercial loads [17]. The second area is dedicated to industrial use and comprises a diesel generator, a wind farm providing renewable energy, and an industrial load. Diesel generators balance the power consumed with the power produced. It is worth noting that this division allows the microgrid to address the energy needs of various sectors while utilizing different sources of power generation.

2. Distributed Control Methodology

The diesel-powered generators in the microgrid ensure stable nominal voltage and frequency to provide uninterrupted power to the loads. It is crucial to avoid overloading the inverters to maintain stable voltage and current and ensure system reliability [18]. A well-designed load management plan is necessary to handle load changes in a controlled and effective manner without compromising power supply stability and quality. Hierarchical control techniques enable efficient load management strategies and optimal system performance.

The proposed hierarchical control structure distributes control across multiple layers, allowing for a decentralized approach in an isolated microgrid with segmented control areas. Each control area has its own specific set of control layers responsible for implementing area-specific control measures [19].

The lower layers of the control hierarchy focus on fast and local control actions to regulate power flow and maintain system stability in real-time within each area. This includes the primary control layer, which manages power flow at the microgrid level within each area [11, 20].

2.1 Primary Control

Primary control, based on the droop approach (P/f, Q/V), allows multiple AC sources to connect and function as synchronous machines. Using droop control, inverters can regulate the frequency and magnitude of the output voltage, ensuring compliant power flow according to network requirements. Each inverter's power loop efficiently manages power through droop control, minimizing imbalances and enhancing system stability [21–23]. Figure 2 depicts the expression of the droop control system.

a) b)

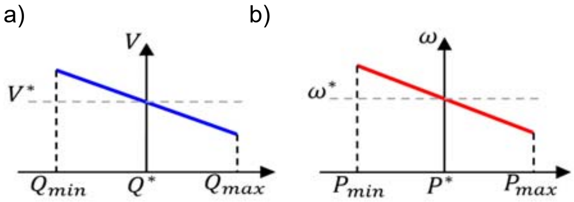

Fig.2. a) Reactive power in relation to voltage,
b) Active power in relation to frequency

The diagram shows the use of a local voltage set point to regulate operating voltage, considering reactive current from capacitive and inductive components. When inductive reactive current is present, the operating voltage increases, requiring a lower voltage set point for compensation. Conversely, in capacitive conditions, the set-point value should be raised. Reactive current variability is limited by maximum reactive power. For large and medium-sized systems, the droop control frequency and voltage can be calculated as follows:

(1) $$V = V^* - n(Q - Q^*)$$

(2) $$\omega = \omega^* - m(P - P^*)$$

where; m and n are the droop control gains.

For large and medium systems, the frequency and voltage of droop control are determined through a standard approach. This approach includes establishing reference values for system frequency and voltage and introducing a droop factor that governs the deviation from these references [24, 25].

The droop factor is a proportional factor that influences the rate at which frequency and voltage change in response to power demand fluctuations. It determines the sensitivity of the control system to load changes. A higher droop factor leads to faster frequency and voltage response to power variations.

2.2 Secondary Control

Secondary control is implemented to address amplitude and frequency deviations that may occur due to primary control. Additional control loops are introduced at a slower time scale compared to primary control, enabling precise regulation of system parameters.

The frequency loop detects any discrepancies between the system frequency and grid frequency, making necessary adjustments. To incorporate secondary control into the primary layer, a low-pass filter is commonly utilized. This filter smooths out high-frequency noise or fluctuations in the secondary control signal, ensuring appropriate response to system changes. The secondary control signal is represented as a variable [26].

(3) $$\delta = \frac{k_i}{s + k_i k_0}(\omega^* - \omega)$$

Where: ki and k0 are control parameters.

Voltage loop: In addition to addressing frequency deviations, secondary control also plays a critical role in regulating system voltage. Voltage regulation is particularly important in power systems, as even small deviations from the desired voltage level can lead to significant problems with system stability and performance [27].

To regulate voltage, secondary control introduces additional control loops that operate at a slower time scale than primary control. These loops are designed to adjust the voltage set points for the individual generators in the system in order to maintain a stable and consistent voltage level throughout the system.

(4) $$\psi = \frac{k_i}{s + k_i k_0}(V^* - V)$$

By incorporating secondary control variables, i and ei, in the way described below to remove frequency and voltage variations, the droop relationship (1) and (2) is altered [28]:

(5) $$V = V^* - n(Q - Q^*) + \psi$$

(6) $$\omega = \omega^* - m(P - P^*) + \delta$$

2.3 Tertiary Control

Tertiary control is the highest level of control in a power system hierarchy, responsible for coordinating multiple power systems across a larger geographic area [29, 30]. It optimizes system-wide performance and efficiency, ensuring reliable operation under various conditions [8, 31].

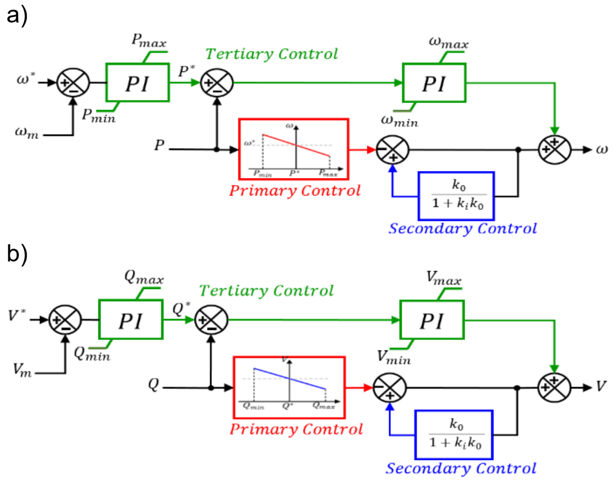

Fig.3. Proposed control scheme for primary, secondary, and tertiary controls a) Frequency loop; b) Voltage loop

Tertiary control enables the import/export of active and reactive power between areas and addresses voltage harmonics of loads through harmonic current injection. The set points of micro-grid inverters can be adjusted to control power flow within the micro-grid, globally or locally.

Figure 3 depicts the proposed control scheme for primary, secondary, and tertiary frequency and voltage controls, which is designed to ensure effective operation of the power system by providing a hierarchical structure of control layers that can respond dynamically to changing energy conditions and optimize the use of available energy resources.

3. System surveyed

The isolated microgrid simulation model developed in this study was used to evaluate a new hierarchical control method for distributed generation control. The micro-grid simulation system consists of four production units, including two renewable energy production units, namely a photovoltaic (PV) unit and a wind turbine unit, both of which are connected to the AC bus.

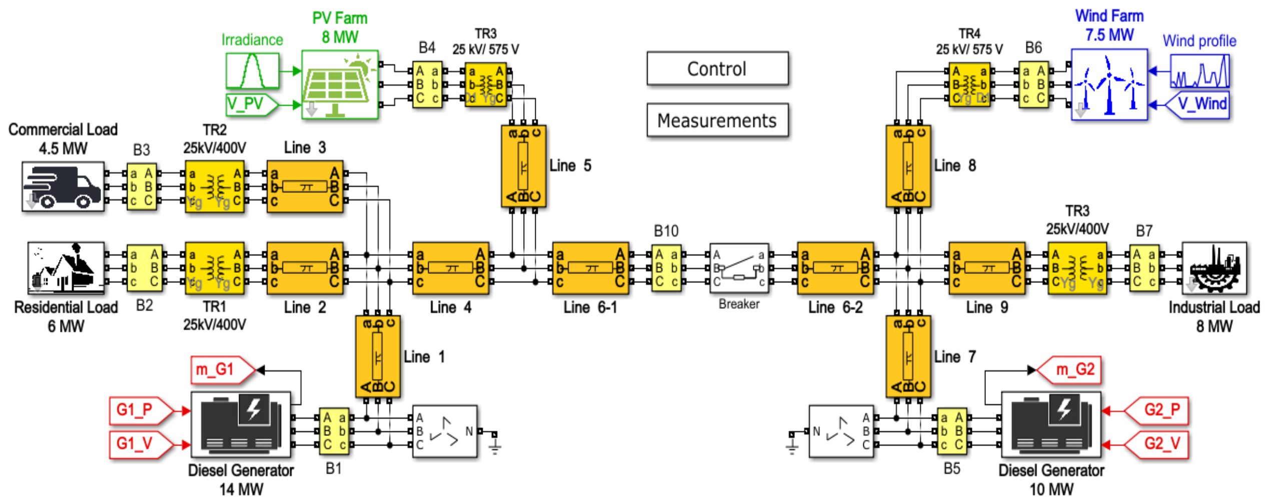

Fig. 4. Proposed Diagram representing an Isolated Micro-Grid with Two Areas

Figure 4 shows the AC bus supporting three non-linear loads in a balanced three-phase system. Residential, commercial, and industrial loads represent concentrated consumption points, and their load profiles mimic realistic consumer behavior patterns over 24 hours. The control scheme was implemented and tested in Matlab to evaluate its effectiveness in regulating voltage, frequency, power balance, and efficient power flow in the microgrid.

In the isolated microgrid simulation model, electricity production is based on two areas. Area 1 includes a 14 MW diesel generator as the base load and an 8 MW photovoltaic park. The energy produced by the photovoltaic park depends on the park size, solar panel efficiency, and irradiance data, which follow a normal distribution with peak irradiance at noon. Area 2 includes a 10 MW diesel generator and an 8 MW wind park with 20% wind penetration. The electric energy produced by the wind park is linearly related to wind speed, with the wind park disconnecting when the wind speed exceeds the maximum value. The wind speed varies throughout the day.

The behavior of diesel generators in the simulation model is modeled with governor systems controlling turbine speed. The inertia constants of all rotating machines are summed to obtain the equivalent machine on the network. The difference between the total load and generator contributions determines the network frequency using the swing equation.

The load in the isolated microgrid simulation consists of residential, commercial, and industrial loads. The residential load ranges from 2.16 MW to 5.89 MW, peaking in the late afternoon and early evening. The commercial load ranges from 1.01 MW to 4.44 MW, peaking during business hours. The industrial load ranges from 2.4 MW to 7.96 MW, with relatively constant demand throughout the day. Load profiles are designed based on statistical data to reflect realistic consumer behavior and are crucial for evaluating the control scheme's performance and obtaining meaningful results.

4. Simulation results

The demonstration presents the performance of the hierarchically controlled isolated micro-grid during a day with notable peaks in output power. Figure 5(a) shows that the power supply system covers the load demand during the following events:

At 7:00 a.m., the electricity production reaches its maximum value of 15.3 MW, which coincides with the start of industrial and commercial activity (4.34 MW for the commercial load and 9.96 MW for the industrial load); generator 1 and generator 2 reach their maximum output power of 7.7 MW and 5.84 MW, respectively.

At 12:00 p.m., the PV reaches its maximum power of 6.26 MW, which relieves diesel production, specifically generator 1.

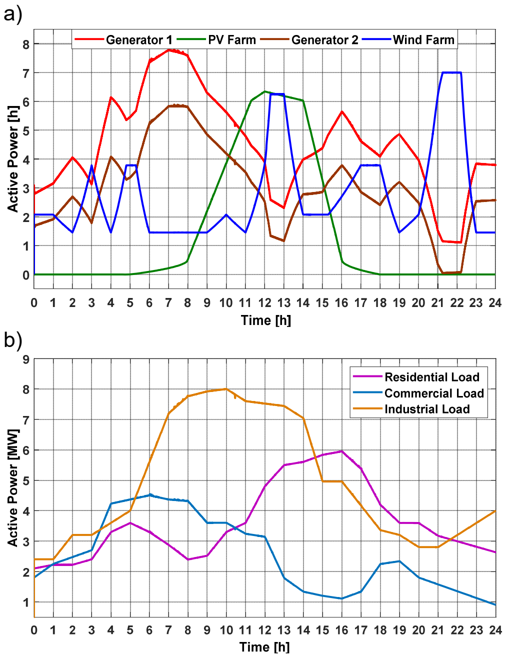

Fig.5. Active power using:
a) Production units; b) Different types of loads.

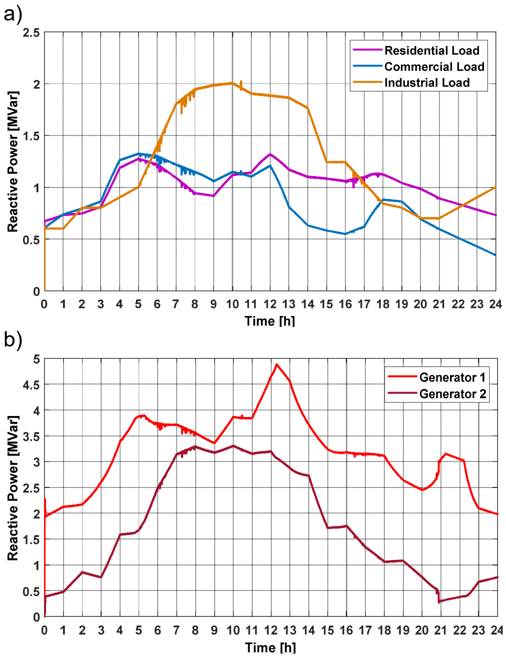

Fig.6. Reactive power:
a) Production units; b) Different types of loads

At 7:00 a.m., the electricity production reaches its maximum value of 15.3 MW, which coincides with the start of industrial and commercial activity (4.34 MW for the commercial load and 9.96 MW for the industrial load); generator 1 and generator 2 reach their maximum output power of 7.7 MW and 5.84 MW, respectively.

At 12:00 p.m., the PV reaches its maximum power of 6.26 MW, which relieves diesel production, specifically generator 1.

At 3:00 p.m., generator 1 records another increase in active power of 5.06 MW, which is due to the temperature effect on the solar panel.

At 9:00 p.m., the wind farm, which generates 7 MW, is able to carry 85% of the load. At this time, as shown in Figure 5(b), the residential load reaches its maximum power demand of 3.08 MW.

Overall, the renewable sources' (PV and wind) output power effectively contributed to relieving the diesel generators and satisfying the consumption peaks.

Additionally, Figure 6 depicts the production and consumption of reactive energy that is only possible with diesel generators, of which generator 1 accounts for 60%.

The study aimed to investigate the effectiveness of the secondary control approach in eliminating frequency fluctuations in an isolated microgrid. The stability of the microgrid's frequency under hierarchical control was analysed for a 24-hour period. The simulation results showed that the proposed control approach ensures a stable frequency even under varying load conditions.

Figure 7 provided further details on the frequency variation of the microgrid's generators. Generator 1 exhibited a frequency variation between 60.004 and 59.996 Hz, while generator 2 had a frequency variation between 60.002 and 58.998 Hz. However, despite fluctuations in the load, the control system was able to restore the frequency to 60 Hz.

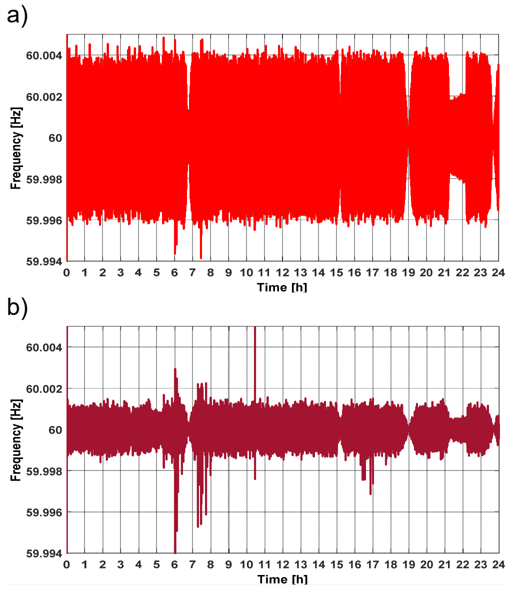

Fig.7. Frequency fluctuation under hierarchical control:
a) Production unit area 1; b) Production unit area 2.

The proposed control approach ensured a suitable working frequency in steady state and transient scenarios. Transient fluctuations in power did not significantly impact the frequency due to the implemented frequency threshold.

The analysis results confirmed the effectiveness of the hierarchical control approach in maintaining a stable and reliable frequency in the isolated microgrid. This is essential for the proper operation of the microgrid's equipment.

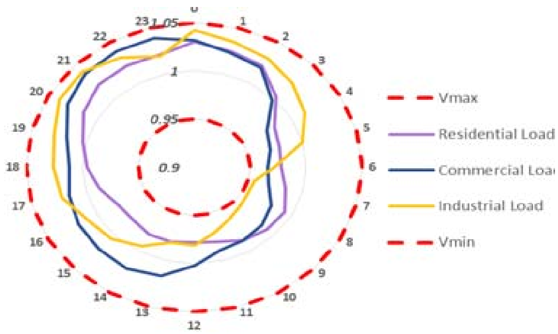

Fig.8. Voltage variation at consumption points under hierarchical management

The load voltage stability is depicted in Figure 8, showing stable voltage levels with minor fluctuations. The highest voltage recorded is 1.042 at the industrial load, while the lowest voltage is 0.955 at the commercial load. Load voltage variations are within the acceptable range of +/- 5%.

Figure 9 displays the DC voltage for the PV and wind farms over a 24-hour period, showing some voltage variations.

For the PV farm, the voltage started at 496.50 V and gradually decreased to 492.85 V throughout the day, with small fluctuations.

The wind farm exhibited voltage fluctuations between 498.13 V and 525.12 V, with no clear overall trend, starting at 505.78 V.

Fluctuations in voltage are normal for renewable energy systems like PV and wind farms, influenced by factors such as weather conditions, sunlight, wind, and load demand. Managing these fluctuations within a certain range ensures system stability and reliability.

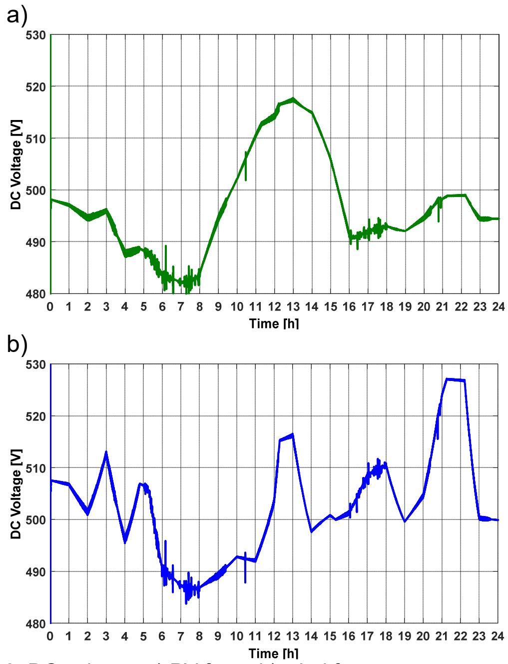

Fig.9. DC voltage: a) PV farm, b) wind farm.

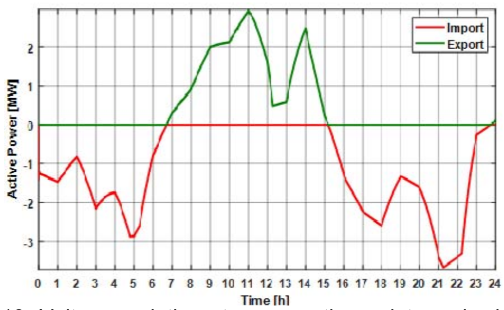

Fig.10. Voltage variation at consumption points under hierarchical management.

Figure 10 illustrates the effectiveness of hierarchical control, specifically the tertiary layer. It can be observed that between 15:15 and 6:40 the next morning, Area 1 imported energy from Area 2. This can be attributed to the absence of photovoltaic production during this period and an increase in the load in Area 1, reaching 8 MW at 5:00. However, during the other period, Area 1 is relieved by renewable production, allowing it to export energy outside its perimeter. The tertiary layer of hierarchical control was able to manage the energy flow in Area 1 efficiently, ensuring that it received the required energy during peak load periods and exported excess energy during off-peak periods.

5. Conclusions

In order to identify the shortcomings of current control techniques, this study analyzes and researches the efficacy of hierarchical control systems in a remote microgrid. It has been shown that the suggested hierarchical control technique is effective in obtaining the best load sharing, voltage, and frequency regulation. Due to the decentralized control strategy's modification of the static control parameters based on pertinent local data, isolated microgrids' frequency restoration and reactive power sharing are now more accurate.

The findings demonstrate that static method-controlled microgrids can operate as flexible microgrids by adapting to challenging daylight conditions during peak hours or unique weather conditions. Overall, the proposed multi-level loop control concept, which is developed as a hierarchical control approach, makes this study more helpful for the development of micro-grid control technology.

The main, secondary, and tertiary control levels perform crucial tasks for an AC microgrid, including enabling the connection of various alternating current sources, particularly renewable energy sources, limiting amplitude and frequency deviation, and facilitating power import and export. The tertiary control level also allows for the import and export of active and reactive power between various network zones while detecting faults, voltage decreases, and power shortages and establishing required repairs. These results open up new directions for further study to enhance the functionality and dependability of microgrid systems.

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