Power-Domain NOMA for Massive Connectivity in Smart Grid Communication Networks

M. Jayachandran and C. Kalaiarasy

Abstract The exploitation of information and communication technology (ICT) and the development of smart electricity networks have become the main concerns worldwide. To leverage ICT in the existing electrical power network, 5G wireless systems are integrated toward the development of smart grid networks. For reliable, efficient, and secure communication infrastructure in a smarter electricity network, the non-orthogonal asynchronous transmission is essential. Besides, a massive number of smart meters (SMs) measure energy consumption and convey instantaneous information to the utility through communications networks. However, data rates beyond 10 Gbps, connectivity to support 1 million per sq km device density, and sub-millisecond latencies are challenging issues when implementing a smart distribution grid. Therefore, this paper presents the non-orthogonal multiple access (NOMA) scheme and optimized power control strategy for smart microgrids to integrate numerous sensor devices with higher data transfer rates and lower latencies. This new microgrid configuration enables multiple electricity users to transmit and receive data simultaneously using the same frequency and enables optimized power flow with high flexibility.

Keywords 5G technology · NOMA · ICT

1 Introduction

The increase of power demand in the existing power network causes severe challenges in ensuring reliable, efficient, and economic operation. Lack of intelligent mechanisms, the conventional grids prone to power outages and blackouts. Therefore, smart grids have gained significant popularity in recent years [1]. Smart grid is an advanced electricity supply network that enables monitoring, sensing, control, and

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C. Subramani et al. (eds.), *Proceedings of International Conference on Power Electronics and Renewable Energy Systems*, Lecture Notes in Electrical Engineering 795,
https://doi.org/10.1007/978-981-16-4943-1_19

communication for improving the reliability, safety, and efficiency of power system operation. In this regard, modern digital communication technologies are essential for the reliable and efficient functioning of the smart grid network (SGN) [2, 3].

Wireless communication technologies are becoming more popular for smart grid applications due to their flexibility and low infrastructure costs. Compared with the 4G technology, 5G has higher system capacity, throughput, and energy efficiency per service. Multiple access (MA) techniques can be regarded as one of the most fundamental enablers in wireless networks. They can be categorized into orthogonal multiple access (OMA) and NOMA methods. In OMA schemes like FDMA, TDMA, CDMA, and OFDMA, multiple users are not permitted to share the same resource concurrently in frequency, time, code, and subcarrier domains, respectively. On the contrary, simultaneous sharing of resources leads to signal interference resulting in loss of data. For instance, an OFDMA network with 64 subcarriers allows only 64 users simultaneously. This orthogonality imposes the capacity limitation. This problem can be resolved by allowing the simultaneous transmission of multiple users in the same frequency carrier which is termed as NOMA. Recently, NOMA has been recognized as one of the promising multiple access techniques for 5G wireless networks. NOMA utilizes the power division multiple access techniques (PDMA) which allocate different power to different users and depends on their distance from the base station (BS) and channel condition [4]. NOMA schemes can be classified into two categories, namely code-domain NOMA and power-domain NOMA. Recently, power-domain NOMA has been proposed which exposes superior capacity than OMA. [5] The fundamental concept of power-domain NOMA is to ascertain that multiple users can be shared simultaneously within the same radio spectrum [6]. The successful operation of NOMA is to form clusters of users with different channel gains and allow them to transmit on the same radio spectrum with appropriate power using superposition coding (SC) at the transmitter and decode the message signal of different users at the receiver using successive interference cancelation (SIC) [7].

Considering the performance of NOMA in fading channels, NOMA in additive white Gaussian noise (AWGN) channels has recently investigated to exploit the time-varying nature of multi-user channels. It has been reported that NOMA achieves superior performance than OMA for various distances [8]. Recently, hierarchical control is proposed for the microgrids. Energy management system (EMS) in microgrids consists of three levels of hierarchical control system, namely primary, secondary, and tertiary control. To optimize the microgrid resources and manage the power flow between the microgrid and the grid, tertiary control is performed.

In this paper, a communication-enabled smart microgrid infrastructure along with an optimized control technique using model predictive control (MPC) for the tertiary control level is proposed. This smart microgrid configuration and the associated control aim to achieve a fast and smooth grid connection of renewable as well as a distributed power source.

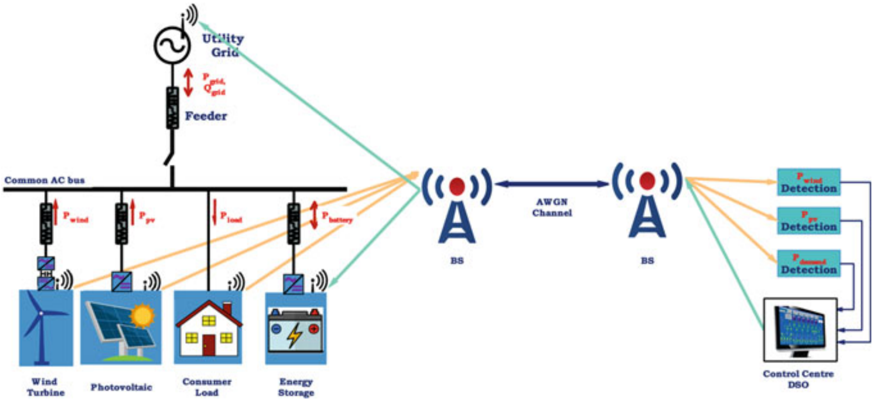

Fig. 1 Schematic diagram of smart microgrid system with wireless communication

2 System Description

The proposed smart microgrid configuration comprises a solar PV array, a wind turbine, a battery energy storage system, and an electric load. All the units in this system are parallelly connected to the common AC bus and rely on wireless communication as shown in Fig. 1. Solar PV and wind turbine are renewable power generation units. The battery bank is an energy storage system that can smooth the intermittent performance of RES and fluctuating load profile. To monitor the smart grid, smart meters are installed for monitoring and measuring the real power, reactive powers, and power flows. In this system, the power converters play a key role to optimize the power flow between renewable sources and the grid.

3 a Typical NOMA Scheme

Concerning uplink transmission with a base station and N devices, smart grid units send messages U_1, U_2, … U_n to the base station. Then, the base station performs superposition coding with these data and transmits the following NOMA signal into the channel:

$$U_{\text{NOMA}} = \sqrt{p}[\sqrt{p}U_1 + \sqrt{p}U_2 + \cdots + \sqrt{p_n}U_n] \tag{1}$$

where P is the total transmit power. Since the channel conditions are arranged as $|g_1|^2 < |g_2|^2 < \ldots |g_n|^2$, the power allocation coefficients must be ordered as $p_1 > p_2 > \ldots p_n$. At the receiving end, device 1 with channel h_1 is farthest from the base station which receives the weakest signal. Device 2 is the next and so on. Device N is the nearest base station that receives the strongest signal. The received

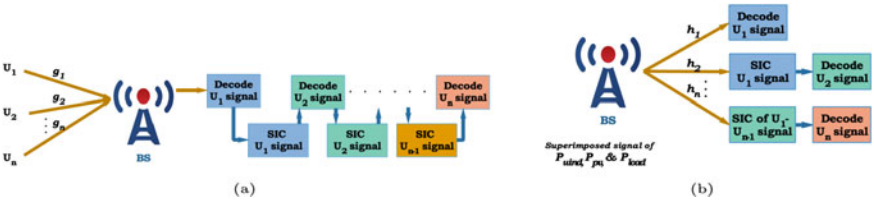

Fig. 2 **a** Uplink NOMA transmission, **b** downlink NOMA transmission

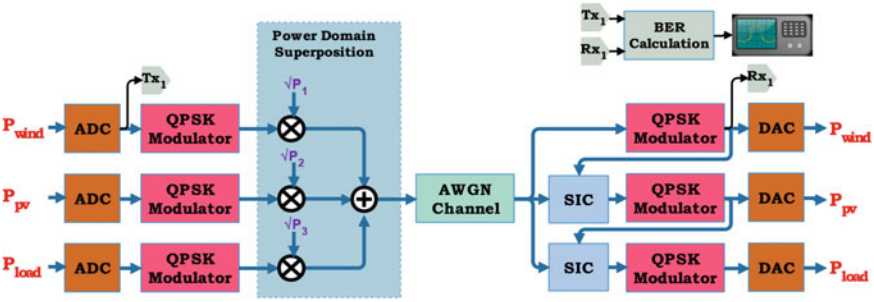

Fig. 3 NOMA with QPSK modulation in AWGN channel

signal at the device i is given by

$$\begin{aligned} Y_{i,\text{NOMA}} &= U_{\text{NOMA}} \times h_i + w_i \\ Y_{i,\text{NOMA}} &= \sqrt{p}\left[\sqrt{p_1}U_1 + \sqrt{p_2}U_2 + \cdots + \sqrt{p_n}U_n\right] \times\ h_i + w_i \end{aligned} \tag{2}$$

where w_i is the additive white Gaussian noise. The channel conditions are arranged as $|h_1|^2 < |h_2|^2 < \ldots |h_n|^2$. Since the highest power is allotted to device 1, this message dominates the received signal. Hence, decoding is performed to obtain the message. Next, the device 2 signal is directly decoded device 1's message, and then, perform successive interference cancelation (SIC) to remove device 1 message. After SIC, the device 2 message is dominating term. Then, perform direct decoding to obtain the device 2 message. This decoding process can be extended to obtain all messages from smart grid units (Figs. 2 and 3).

4 The Proposed Power Control Strategy

With the knowledge of power demand (P_{demand}), the solar PV power (P_{pv}), and wind turbine power (P_{wind}), the net power available in the common AC bus as shown in Fig. 4 can be calculated as

Fig. 4 Model predictive control for power management strategy

$$P_{\text{net}} = P_{\text{pv}} + P_{\text{wind}} - P_{\text{demand}} \tag{3}$$

For energy saving considerations, this net power must be balanced through battery energy storage system (BESS) power (P_{BESS}) and the utility grid power (P_{grid}). When inverter power is negative, the battery absorbs power from renewable energy sources. Conversely, when inverter power is positive, the battery supplies power to the load. In discharging mode operation, a battery with the higher state of charge (SoC) supplies more power, whereas lower SoC supplies less power. The converse is also true in the charging process. The SoC of BESS can be obtained as

$$\text{SoC}(k+1) = \frac{\text{SoC}(k) + P_{\text{BESS}}(k+1) \times Ts}{C_{\text{BESS}}} \tag{4}$$

where C_{BESS} is the capacity of the batteries. The battery power and utility grid power can be predicted at the next control instant as

$$P_{\text{BESS}}(k+1) = u(k+1) + P_{\text{BESS}}(k) \tag{5}$$

where the control variable $u(k+1)$ is the change of battery power. The required battery power (P_{net}) is obtained by minimizing the following cost function to keep the power balanced within microgrid as

$$J = |\, P_{\text{net}}(k+1) - P_{\text{BESS}}(k+1)| \tag{6}$$

In general, the microgrid and utility can operate at different frequencies. The transition from islanded to the grid-connected mode and grid-connected to islanded mode are typically planned. To realize a smooth mode transfer, a synchronization procedure is performed to synchronize the voltage, phase angle, and frequency of the DG unit to the common AC bus at the utility side. The proposed control strategy maintains the terminal voltage and frequency of the units to their nominal values. Hence, the units deliver their nominal active and reactive power to load.

5 Simulation Results

Due to simultaneous transmission, NOMA suffers from interference. As a result, OMA performs slightly better than NOMA at low SNR as shown in Fig. 5a. However,

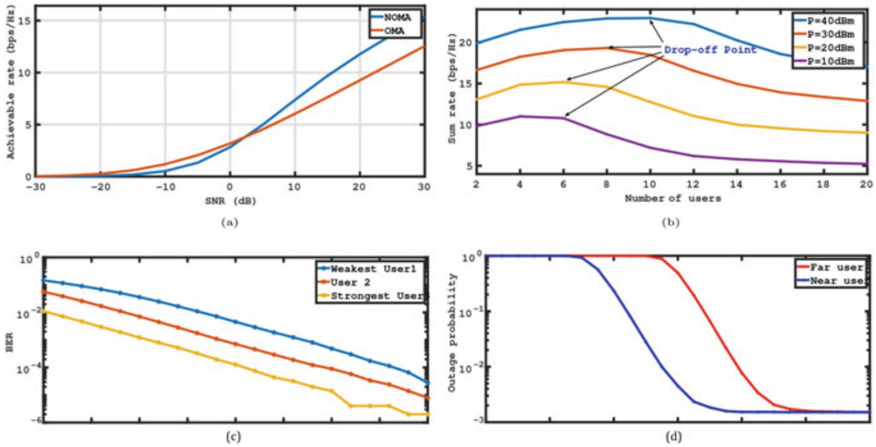

Fig. 5 **a** Capacity performance comparison of NOMA vs OMA, **b** A power allocation method for multiple user single-carrier NOMA, **c** BER performance of multiple user NOMA with QPSK modulation in AWGN channel; **d** Outage probability of uplink NOMA

NOMA outperforms OMA by offering high capacity at high SNR. As a consequence of the number of users (i.e., smart grid devices) of single-career NOMA is increased, the capacity of the network initially increases as shown in Fig. 5b. The drop-off point may be regarded as the maximum limit on the number of devices that can be admitted into the network without any performance degradation. Beyond the drop-point capacity falls. The drop-off point can be changed by varying transmit power. In order to enhance the network capacity without performance degradation, transmit power should be increased. However, the fixed power allocation scheme affects the BER performance as shown in Fig. 5c. The weakest signal has the highest bit error rate, while the strongest signal has the lowest BER and is free from interference. The outage probability is high for both near and far users as shown in Fig. 5d. Thus, NOMA gives superior performance when the channel conditions between the users are more distinct.

Besides, the performance of the proposed control strategy is analyzed in a case study. A typical load profile consumption per day is depicted in Fig. 6a. The power demand throughout the year is also presented in Fig. 6b, and the average load demand for this site is approximately 4 kW. The wind and solar meteorological data for Sundarban (India) location are considered for the case study as shown in Fig. 6c, d. It is observed from Fig. 6g that the power generated by PV is more than the power demand during June–September (3651-6570 h). Hence, the utility grid has not contributed. This excess energy is utilized to charge the battery and distribute it into the dump load as shown in Fig. 6e. It is noted that high quantities of dump energy are stored in the battery (77.19 kW). It can be utilized for street lighting, heating, water pumping, and refrigeration. It is clear from Fig. 6f that the depth of discharge is maintained up to 80% and the state of charge of the battery is not less than 20%

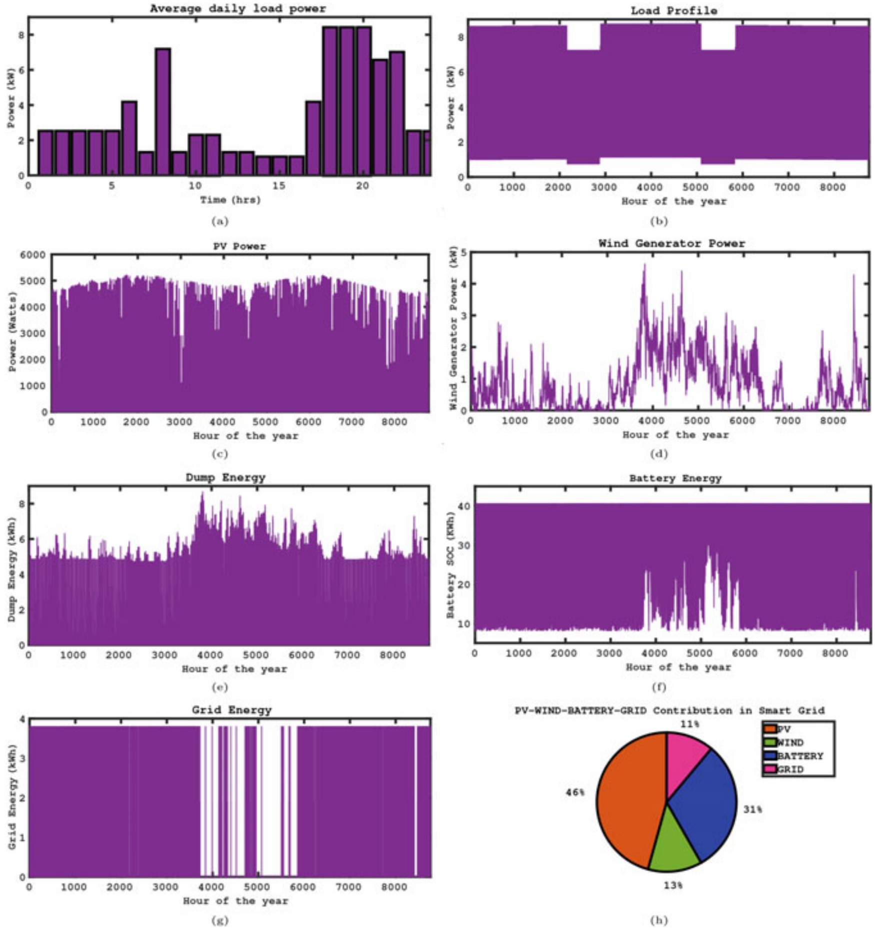

Fig. 6 **a** Typical load profile consumption per day, **b** hourly power demand, **c** hourly PV power, **d** hourly wind turbine power, **e** battery dump energy during the year, **f** battery energy during the year, **g** utility output energy; **h** energy contribution of PV, WT, BESS, and utility grid

of charge level. The percentage of contribution of units over a year is depicted in the pie chart in Fig. 6h.

6 Conclusion

A NOMA-based smart microgrid configuration and MPC-based power control scheme are proposed for future microgrids. The performance and benefits of adopting NOMA can support massive connectivity with high data rates and low latencies for smart grid communication systems. Besides, the proposed power management strategy optimizes power flow within the microgrid and between renewable energy sources and the utility grid. Thus, the proposed smart microgrid system provides high-quality and reliable electricity to the customers irrespective of the fluctuated renewable energy sources.

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