Evaluation of the Impact of Rooftop Solar Power on the Power Quality of Vietnam Urban Distribution Networks according to Relevant Vietnamese and IEEE and IEC Standards

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Received: 18 February 2024 | Revised: 6 March 2024 and 26 March 2024 | Accepted: 30 March 2024

 | DOI: https://doi.org/10.48084/etasr.7099

ABSTRACT

The goal of reducing greenhouse gas emissions and energy transition has created many favorable conditions to promote solar power generation technology. However, from a technical perspective, integrating solar power into the power grid poses many challenges in grid operation. This study investigates the impact of rooftop solar power in terms of power quality in the urban distribution grid in Vietnam. The current study simulated a typical low-voltage distribution grid with single-phase and three-phase loads to evaluate important power quality issues, such as Total Harmonic Distortion (THD) of voltage and current, voltage unbalance, and voltage rises. A grid simulation grid was developed in Matlab/Simulink under different conditions for the penetration level of solar power and the daily variation of loads. These indexes were compared with the limits specified in Vietnamese standards and the relevant international standards of IEEE and IEC. Compliance with the provisions of these standards was provided, even in the case of solar power systems with a high level of penetration into Vietnam's urban distribution grid.

Keywords-harmonic distortion; penetration level; photovoltaic distributed generation; power quality; voltage unbalance; voltage rise; rooftop solar; urban distribution network

I. INTRODUCTION

The interest in developing solar power sources has increased in many countries around the world. Solar power has the highest growth rate among renewable power generation technologies. The installed solar power capacity in 2022 has reached 239 GW, representing 66% of the total installed capacity of the renewable energy sources [1]. In recent years, renewable energy-based power sources have continued to grow but their contribution is still limited, accounting for only 4.5% of the global electricity production. Vietnam is the leading country in the solar power development in Southeast Asia, with the installed capacity reaching approximately 19 GW in 2022 [1]. Practical implementation shows that government policy mechanisms and preferential price policies play a pivotal role in promoting renewable energy sources, in addition to the available natural potential or the climate conditions [2-3]. Furthermore, technical issues must be thoroughly resolved so as not to cause negative impacts on the existing power system [4-8]. For instance, in [9], partial shading issues were addressed, where different interconnected fixed-building integrated photovoltaic arrays were introduced to improve the maximum power of large PV systems. In addition to areas such as the south-central coastal region of Vietnam, many other areas have significant potential for rooftop solar power development. Integrating solar power into the urban power grid is an issue of concern in the context of meeting local energy needs. In this situation, the issue of power quality in the distribution network has attracted a lot of attention. Increased penetration levels have many potential impacts on the operation of the distribution grid. The PV panels of the rooftop solar power systems are often connected to the grid via power electronic converters and in a single-phase configuration, often causing power quality problems, including reliability, unbalance of current and voltage, harmonic distortion, and voltage rise. Therefore, this is an obstacle when it is necessary to increase the penetration level of solar power.

Large-scale rooftop solar power systems have the following impacts on the urban distribution grid:

- Voltage rise, fluctuations, and unbalance
- Increase of harmonic levels, affecting power quality
- Other effects such as overload and impact on the protection system.

Voltage-related problems include voltage fluctuations, voltage increases or decreases, and voltage unbalance. These problems cause damage to voltage regulation devices, such as on-load tap changers of transformers, capacitor banks, overvoltage and overcurrent protection devices, and fluctuations in reactive power flow due to failure. As a consequence, new requirements are needed for the regulation of voltage and reactive power [10-13]. Voltage rise is one of the most serious problems, often occurring when a PV source and a small residential area are powered by the same distribution transformer. In the traditional distribution network with radial configuration (or mesh configuration networks operating in open loops), the power flow is in the direction from the feeder to the load. In normal operation, the drop voltage across the line impedance causes the load voltage to be lower than the feeder one. To maintain the voltage at the load nodes within the allowable range, it is necessary to use reactive power compensation devices, such as fixed or controlled capacitors and tap changers of power transformers. There is also a problem of voltage fluctuations and reactive power [13]. Voltage rise often appears when PV systems generate high power but the load's power consumption demand is low. The increase and fluctuation of the voltage have a direct impact on the equipment in the power grid. Voltage changes cause voltage regulators to operate more frequently to maintain the power supply to the load. As a result, the service life of these devices is reduced, increasing the need for repair and maintenance.

An evaluation of the change in the power source has displayed that when the power input to the grid increases, the voltage in some areas of the system may exceed the allowable range. The voltage rise is at the highest level when the local load has the lowest demand (or no load). Then, most of the power is sent to the primary side of the connection station. This is also the period that indicates the PV output capacity limit without causing the voltage to increase beyond the allowable limit. In addition, during this period, it is necessary to evaluate the voltage regulation capacity of the connected transformer when the power flows back into the main grid, which can be called the power backflow phenomenon [14]. In [15], it was demonstrated that with a low penetration level, the PV system improved the voltage by up to 0.51% at the rated voltage of 22.8 kV. High voltage rise in a steady state is the most prominent problem that needs to be addressed in the distribution grids with PV sources, especially in cases where these sources have large capacities.

An inherent characteristic of the power distribution grid is the asymmetry of the line phase parameters (R and X). It should be noted that these parameters are not balanced as in a transmission system by phase transposition. Another cause of imbalance in the distribution network is the presence of single-phase loads that cause the load capacity in the three phases to be unequal. The integration of PV sources may make this problem more severe [16]. The installation of PV sources in the power grid is mainly based on customer needs, so the location and capacity of these sources are highly random and depend on the customer's wishes [17]. Furthermore, harmonics generated during the operation of the inverter affect power quality because of harmonic pollution. Therefore, proper evaluation is needed to limit the unexpected effects due to voltage and the current harmonics that affect energy loss and transmission efficiency. As a common consequence, harmonics can shorten equipment life and reduce the load capacity of lines and transformers.

The impact of solar power on the distribution grid has received much attention. Various approaches, such as numerical and analytical methods, or methods based on uncertainty models have been applied to evaluate the impact of rooftop solar power on the electricity quality of the low voltage distribution grids, focusing on voltage unbalance, voltage rising, and voltage harmonic distortion [18]. In [19], power quality was assessed and compared in two cases for the grid, with and without PV, by PCC measurements. The total current harmonic distortion (THD_i) exceeded 45% of the fundamental during periods of high PV generation power, with the main reason being the low value of the fundamental current. Furthermore, because of the operation of the inverter, the 40th harmonic corresponding to the switching frequency in the component frequency spectrum of the current increased significantly. Voltage harmonic distortion (THD_u) tends to increase sharply during periods of low PV capacity. In [20], a system design that included electric vehicles was proposed in a low-voltage network with a high penetration of PV systems. Rapid changes in PV system power output can cause significant flickers during the day. This study examined scenarios in three different years and proposed solutions to limit this impact by changing the discharge mode, allowing to significantly reduce the amount of visible and annoying light flickers. In [21], a comprehensive modeling and analysis for low and medium-voltage distribution networks was introduced, allowing online evaluation of the effects of PV panels. The main index reported was the voltage value of the nodes in the selected power grid. In [22], power quality issues due to the large penetration of PV systems affecting a feeder in Sri Lanka were examined. The issues considered included harmonic distortions, voltage rises, and Direct Current (DC) injection into the main grid. Analytical simulation results were compared with the limits specified in several global regulations. In [23], a diagram consisting of four PV systems connected to two substations was studied for power quality regarding the provisions of the EN 50160 standard. The results revealed that the short-circuit power can cause the power quality index to be violated, especially in terms of harmonic distortion in low-power operations. In general, PV system controllers are constantly being improved to ensure better power quality and minimize the impact on the main grid [24].

Although there are several studies analyzing the effects of the rooftop solar power on the power system [25-26], there has been no research evaluating grid power quality issues when integrating many rooftop solar power systems into Vietnam's urban power grid. This study focuses on evaluating the impact of large-scale integration of rooftop solar power systems on the urban power grid in Vietnam in terms of power quality. The key contributions of this study are: (1) to identify the typical configuration of distribution grids integrating rooftop solar power systems and typical cases related to power quality in Vietnamese urban areas, (2) to simulate and determine the power quality index and current and voltage THD levels at the nodes, (3) to evaluate these power quality results according to the relevant Vietnamese and IEEE/IEC standards, and (4) to provide several recommendations and suggestions based on these findings. Therefore, this study is essential for policymakers and grid operators in Vietnam.

II. CASE STUDY OF URBAN DISTRIBUTION NETWORK

Vietnam's urban distribution network is designed with a meshed configuration but operated radially in an open loop. Therefore, it can be considered as a radial network. Figure 1 shows a typical radial network selected to investigate the impact of rooftop PV systems on the power quality of the distribution networks in the urban areas of Vietnam. The power received from the main grid through a feeder distribution transformer supplies a three-phase load at node $A_1B_1C_1$ to evaluate voltage unbalance, and three single-phase loads at nodes A_2, B_2, and C_2. In addition, there are three PV sources such that PV_A, PV_B, and PV_c are connected to phase A of the three-phase node $A_1B_1C_1$ and single-phase nodes B_2 and C_2, respectively.

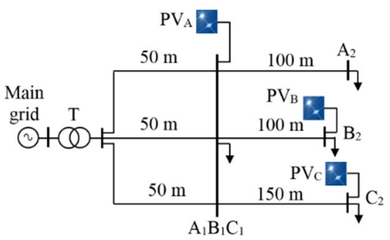

Fig. 1. A typical low-voltage urban radial distribution network in Vietnam during normal operation.

A. *Model of PV System*

Figure 2 presents the block diagram of a two-stage single-phase PV system. A DC-DC boost converter with Maximum Power Point Tracking (MPPT) control is applied to extract the maximum power from the sun. Additionally, the inverter with the DC voltage controller is responsible for keeping the DC voltage constant.

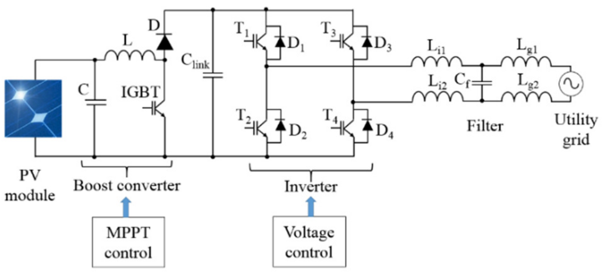

Fig. 2. A two-stage single-phase photovoltaic system.

1) *Model of PV Array*

The single-diode model is sufficiently used to simulate the PV array in this study. The output current of the PV array can be calculated by [27]:

$$I_{PV} = n_p I_{ph} - n_p I_{rs}\left[e^{\frac{qV_{PV}}{kT_C A n_s}} - 1\right] \quad (1)$$

where I_{ph} is the photocurrent of the solar cell, I_{rs} is the cell reverse saturation current, I_{PV} is the PV array output current, V_{PV} is the PV array output voltage, $n_p$is the number of cells connected in parallel, q is the charge of an electron, k is the Boltzmann's constant, T_C is the cell's working temperature (K), A is the p-n junction ideal factor, and n_s is the number of cells connected in series.

2) *Model of Boost Converter with MPPT Controller*

A boost converter is mainly composed of an Insulated-Gate Bipolar Transistor (IGBT) and a diode. Other passive elements include an inductor and a capacitor. The mathematical model of the converter can be expressed by:

$$L\frac{di}{dt} = -(1-u).v + V \quad (2)$$

$$C\frac{dv}{dt} = (1-u).i - \frac{v}{R} \quad (3)$$

where V is the input voltage of the converter, i is the inductance current, v is the capacitor voltage, L, C, and R are the parameters of the circuit, and u is the switch position function of the switch S, u = 0 or 1. The MPPT controller is designed for the boost based on the Incremental Conductance Technique (ICT) [27-28].

3) *Filter*

A filter connects the inverter to the utility grid to filter the harmonics produced by the inverter. It is composed of inductors L_{i1}, L_{i2}, L_{g1}, and L_{g2} and a capacitor C_f.

B. *Models of Power Transformer and Power Line*

Figure 3(a) portrays the equivalent circuit of a power transformer, composed of three branches, presenting the primary winding (R_1, X_1), the secondary winding (R_2', X_2'), and the iron core (R_m, X_m), respectively.

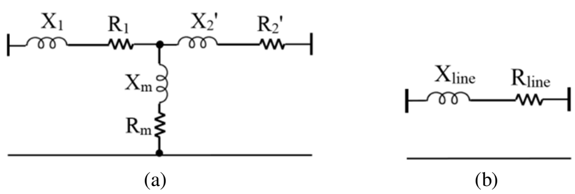

Fig. 3. Equivalent circuits of (a) power transformer and (b) low voltage power line.

The parameters of resistances and reactances can be computed according to the catalog data, including the nominal apparent power, short-circuit power loss, no-load power loss, primary nominal voltage, short-circuit voltage, and no-load current. The model for the low voltage distribution line solely includes a series resistance and a reactance, as displayed in Figure 3(b). These parameters can be calculated by:

$$R_{line} = r_0.l; \quad X_{line} = x_0.l \tag{3}$$

where r_0 is the series resistance per unit length (Ω/km), x_0 is the reactance per unit length (Ω/km), which can be computed from inductance per unit length (H/km), and l is the length of the line.

III. SIMULATION RESULTS AND DISCUSSION

The simulation was developed under the following conditions:

- Typical load curves and power transformer parameters were adopted from [29]. Four different typical daily cases for the load factor and the PV radiation were investigated. Among them, the case with the highest radiation was predicted to be under the most impact of the PV, i.e., load factor of 0.8 and radiation of 776 W/m^2.
- Since the loads in the distribution network are usually located to three phases as balanced as possible, the following capacity is used: A balanced three-phase load connected to node $A_1B_1C_1$ of 135 KW and three single-phase loads of 45 KW connected to nodes A_2, B_2, and C_2.

The impact of the PV source on the power quality is reviewed under different penetration levels. These levels are chosen regarding the practice implementation in the distribution network in Vietnam, as the PV source is authorized to connect to the three phases of the grid as balanced as possible. The PV systems are simulated at four approximate penetration levels, provided in Table I.

TABLE I. LEVELS OF PV PENETRATION

Level	Phases A and B	Phase C	Network
1	0%	24%	8 %
2	24%	47%	32 %
3	47%	71%	55 %
4	71%	95%	79 %

Three criteria are evaluated, including:

- The rise of voltage at the network nodes
- The THD level of current and voltage of nodes
- The unbalance factor at node $A_1B_1C_1$, assuming that the load in the three phases at each node is balanced.

Figure 4 exhibits the voltage cycles at node $A_1B_1C_1$. It can be seen that the voltage signal tends to be more distorted as the PV penetration level increases. Similar comments can be made for the voltages at nodes A_2, B_2, and C_2, noticed in Figure 5. The analysis of the voltage signal indicates that an increase in the penetration of PV causes the voltage THD to increase. At each penetration level, the THD of phase C is the largest, followed by phase A, and the lowest is phase B for node $A_1B_1C_1$. However, the voltage THD of phase A (node A_2) is less than that of phase B (node B_2). The reason is that phase C has the highest penetration level with PV_C, and phases A and B have lower and equal penetration levels. In addition, PV_A is connected directly to phase A of the node $A_1B_1C_1$ whereas PV_B is at node B_2, which is connected to the three-phase node through a distribution line section. In all cases, the voltage THD is within the allowable limit of 8%, which is the maximum acceptable value in the low-voltage distribution network according to Vietnam standards [30].

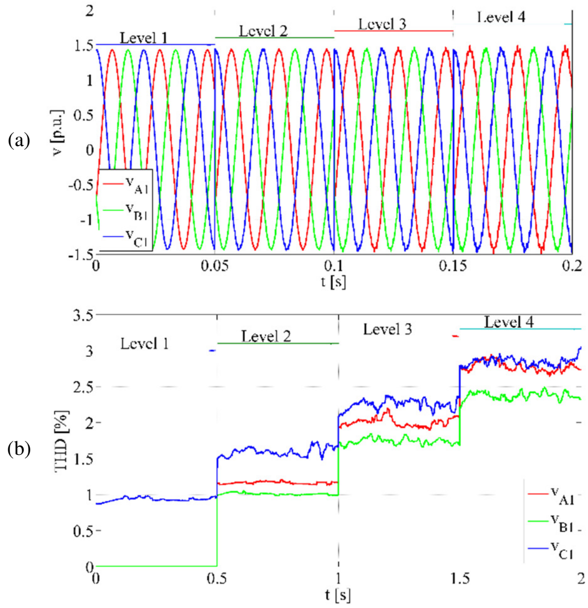

Fig. 4. Node $A_1B_1C_1$: (a) voltage signal and (b) voltage THD.

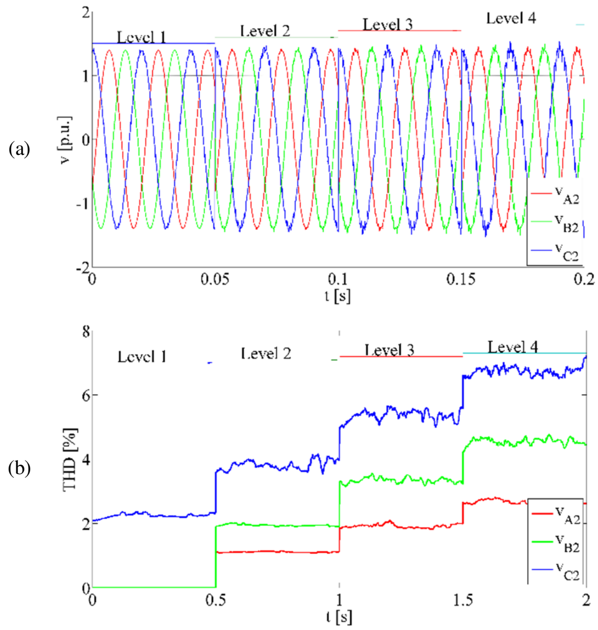

Fig. 5. Nodes A_2, B_2, C_2: (a) voltage signal and (b) voltage THD.

Figure 6 discloses the voltage unbalance ratio at node $A_1B_1C_1$, which is the ratio of the negative sequence component to the positive sequence component of the voltage. According to IEEE 1159 [31], the acceptable limit of this ratio is 2%. In IEC TR6100-3-14, the voltage unbalance index should be below 2% (99% of the weekly measurements for a very short interval of 3 s) [18]. In Vietnam, the ratio of a negative sequence voltage component to the specific nominal voltage grade should not exceed 3% in the normal operating mode of the distribution network [30]. Thus, it can be concluded that the unbalance of about 0.4% is much smaller than the specified limit in the aforementioned regulations.

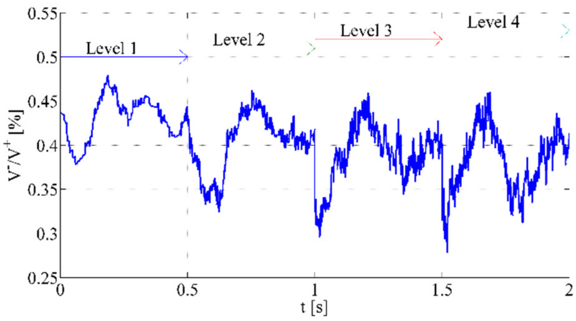

Fig. 6. Voltage unbalance ratio at $A_1B_1C_1$.

Figure 7 presents the THD of the currents fed by the PV sources into the grid. THD maintains a steady mean value following the change in the PV penetration level. Indeed, analyzing the current signal from PV sources for 10 cycles yields a THD of less than 5%, as illustrated in Figure 7(b) for the largest PV_C.

(a)

(b)

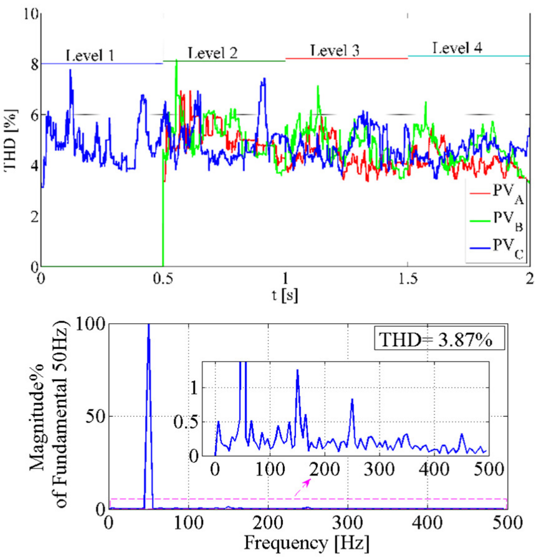

Fig. 7. (a) Instantaneous THD of currents from PV_A, PV_B, and PV_C, (b) THD of current from PV_C.

Compared to the regulations in [30], where the permissible maximum value of the total demand distortion of the current from a power plant is 5% for a low-voltage grade system, it is concluded that the THD level is within the allowable limit. Figure 8 manifests the analysis results of the voltage RMS values (p.u.) at the network nodes in the case of the highest PV penetration, level 4. Figure 8(a) shows that the voltage at node A_2 of phase A is the lowest because there is the only load. Meanwhile, the voltage at phase C is the highest because the PV penetration is the largest and the power flows back toward the feeder. Figure 8(b) suggests that the feeder voltage is quite balanced. According to IEC 60038:2009 [32], the supply voltage under normal operation should be in the range of ±10% around the nominal voltage of the system. In Vietnam, the allowable operating voltage deviation at the connection point compared to the nominal voltage is ±5% at the connection point with electricity consumers and (-5%, +10%) at the connection point to the power plant [30]. Therefore, the results in Figure 8 demonstrate that the voltage values completely meet these regulations.

(a)

(b)

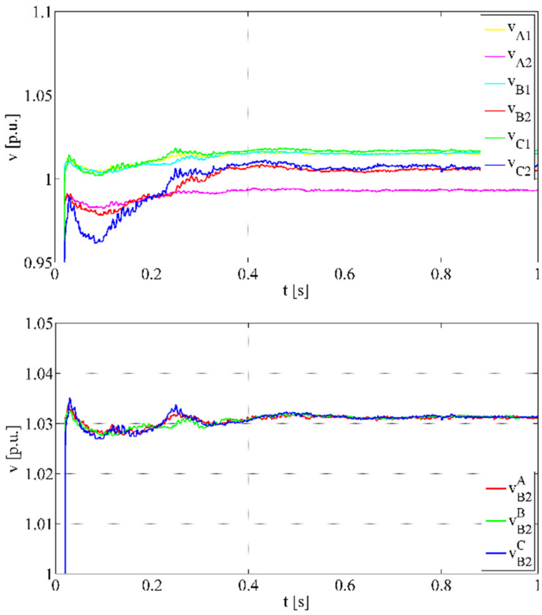

Fig. 8. RMS values of (a) load node voltages and (b) feeder voltage.

The simulation and analysis results exhibit that the THD, voltage unbalance, and voltage rise mostly change with the PV penetration level. Although the penetration level is in a fairly wide range, including quite high levels, the indicators are all within the allowable limits when compared with the limits specified in national and international standards.

IV. CONCLUSIONS

Vietnam is experiencing a rooftop solar power boom with a capacity of almost 10 GW with more than 100,000 systems. Most rooftop solar systems are concentrated in urban areas with a high population density. Rooftop solar systems help to meet part of the high load demand in urban areas, but they can also cause power quality problems when the penetration rate of the solar power is high. In some situations, the penetration rate of the rooftop solar systems could reach 100%. This study evaluated the impact of rooftop solar systems on power quality in the urban power grid in Vietnam. First, the typical configuration of the power grid in Vietnamese urban areas was surveyed under normal operating conditions. Then, mathematical models were built on Matlab/Simulink software.

Typical scenarios with solar power penetration rates were selected, analyzed, and simulated. In these scenarios, the numerical simulation results were compared and analyzed with the current Vietnamese standards as well as the relevant IEEE and IEC standards.

According to the results, the voltage THD was within the allowable limit of 8%, which is in line with the Vietnamese standards. The voltage unbalance when integrating large-scale rooftop solar systems in the urban distribution grid is also within the limits of the Vietnamese and IEEE standards. Additionally, the THD of the currents fed by the PV sources into the grid is less than 5%, which is accepted by the the Vietnamese standards. In summary, when large-scale rooftop solar systems participate in Vietnam's distribution networks, the power quality of the grid is within the acceptable limits of the Vietnamese regulations and the IEEE and IEC standards. In the future, this research will further investigate both analytically and experimentally the impact of high penetration rates of the rooftop solar systems and electric vehicles integrated into urban distribution grids, and the bi-directional effects of the rooftop solar systems under abnormal grid operating conditions.

V. ACKNOWLEDGMENT

This work was supported by the joint project "Research on PV integration for sustainable energy development in urban areas in Vietnam" (NĐT/DE/21/06) funded by the Vietnamese Ministry of Science and Technology and the German Ministry of Education and Research (BMBF).

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