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Mathematical Modelling of the Power Supply System of a Mobile Communication Base Station

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***Abstract:** The Stable operation of mobile communication base stations depends on a continuous and reliable power supply. Power outages can lead to a decrease in communication quality or even complete service interruptions, negatively affecting users and threatening system reliability. Therefore, there is a growing need for energy management approaches based on mathematical modelling to ensure an uninterrupted power supply and improve overall system efficiency. In this article, a mathematical model of the power supply system for a mobile communication base station is developed. Based on the developed mathematical model, the mobile communication base station power supply system was simulated in the Proteus Professional 8.17 SP2 program. The simulation model enabled the simulation of the power source control system under various operating conditions, allowing for the evaluation and analysis of the power supply sources based on these conditions. Based on this model, experimental tests were conducted. The results of these tests demonstrated that the model is capable of providing a rapid response to power interruptions in the base stations, depending on the status of the energy sources, thereby ensuring an uninterrupted power supply. It was also found that utilizing supercapacitors as a primary power source during interruptions reduced the response time by a factor of 10.*

***Keywords:** Energy Optimization, Hybrid Systems, Supercapacitor, Renewable Energy, Solar Panel, Wind Generator, Batteries, Mathematical Model, Uninterruptible Power Supply, Reliability.*

Abbreviations:
ICT: Information And Communication Technology
VSM: Virtual Simulation Modelling
IoT: Internet of Things
EDGE: Enhanced Data rates for GSM Evolution
WCDMA: Wideband Code Division Multiple Access
UMTS: Universal Mobile Telecommunication System
MIMO: Multiple-Input Multiple-Output

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I. INTRODUCTION

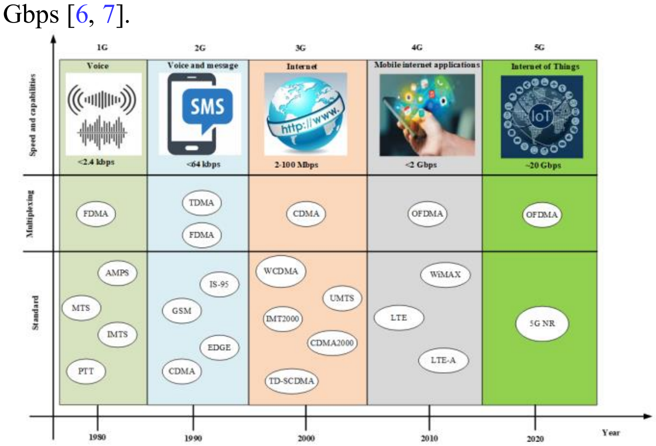
Today, the demand for mobile communications infrastructure is skyrocketing. This places important and urgent tasks on the shoulders of communication operators, such as ensuring network stability and service continuity. As users' needs for high-quality and stable communication services increase, the number of mobile communication base stations is also increasing proportionally. Recent studies in the telecommunications industry have shown that base stations consume a large amount of electricity to operate with high reliability. In particular, according to forecasts by international experts, the number of base stations operating worldwide is expected to exceed 13.1 million by the end of 2025, and their total energy consumption is expected to surpass 200 billion kWh. This accounts for more than 80 per cent of the total energy consumption of the information and communication technology (ICT) sector [1,2]. The continuity of electrical power is one of the essential technological criteria for the efficient and stable operation of mobile communication base stations. Any interruptions in the power supply will lead to disruptions in station functionality, a decrease in the quality of communication services, and disruptions between subscribers. In addition, the economic consequences of power outages are also significant and are manifested in the following aspects [3]:

- Reduced communication quality: As a result of a temporary outage of a base station, users are disconnected from the network, which leads to a decrease in the quality of service for operators.
- Reduced production efficiency: Temporary interruptions in telecom services cause technological disruptions and loss of time in manufacturing industries.
- Additional operating costs: During power outages, the need to use backup power sources (batteries, diesel generators, etc.) increases, which dramatically increases maintenance and operating costs.

In the study [3], the power supply system interruptions at mobile communication base stations were analyzed and evaluated. The results of the analysis show that the interruptions increase over time and it is emphasized that efficient and reliable power supply sources should be used during these interruptions. Therefore, modelling the power supply system of mobile communication base stations, developing algorithms and mechanisms for managing backup sources to ensure its continuity, is recognised as a pressing scientific and technical issue in modern telecommunications systems.

II. MATERIALS AND METHODS

Over the years, as mobile communication technologies have developed, their energy demand has also increased significantly. The following analysis illustrates the increase in energy consumption across the phases of mobile networks, from 1G to 5G, based on technological capabilities, speed ranges, and standards employed (Figure 1). 1G (1980s) was an analogue communication system designed only for voice transmission. This system, which had a speed of around 2.4 kbps, had relatively low power consumption because the device's functionality was limited. 2G (1990s) is considered a transition to digital communication systems. In addition to voice, text messaging (SMS) became possible. Standards such as GSM, IS-95, and EDGE were introduced. Data transfer speeds increased to 64 kbps. At this stage, although energy consumption had increased, it was still at a relatively low level. 3G (2000s) marked the beginning of the mobile internet era, enabling data transmission speeds ranging from 2 Mbps to 100 Mbps. Systems such as WCDMA, UMTS, and CDMA2000 were widely implemented. This phase required networks to be constantly active, which dramatically increased the energy needs of base stations [4, 5]. 4G (2010s) brought real-time streaming of multimedia content, video calls, cloud services, and other high-traffic applications to the forefront. LTE, LTE-A, and WiMAX technologies have achieved speeds of 1–2 Gbps [6, 7].



[Fig.1: Development Stages of Mobile Communication Systems Over the Years]

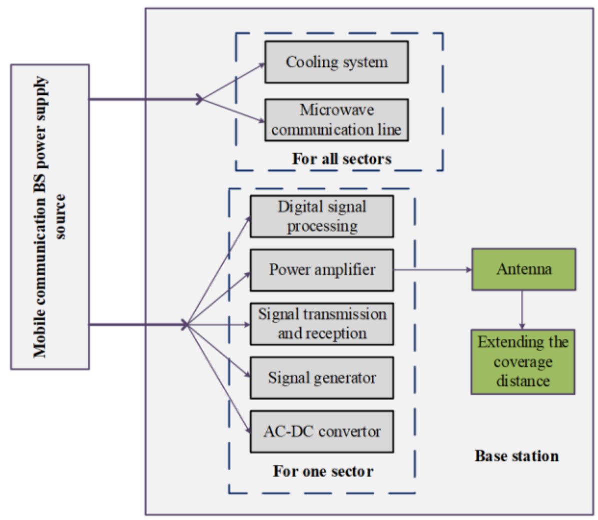
As a result, the number of base stations has increased, and the energy consumption of each station has also increased. 5G (2020s) is designed for industrial automation, the Internet of Things (IoT), smart cities, and ultra-low latency services. Speeds have increased to 20 Gbps. 5G technology uses massive MIMO (multiple antenna systems), beamforming, and operates in higher frequency bands, which results in significantly higher power consumption. Therefore, the operation of 5G networks requires a stable and high-capacity power supply system [8, 9]. As can be seen from the above evolutionary analysis, each new stage of mobile communication technologies has not only improved the quality of service, but also dramatically increased the energy load on base stations. This situation further increases the need to develop modern, uninterrupted, and efficient power supply systems for mobile communication infrastructure [10]. Mobile communication TS consists of several sectors, each of which covers a particular corner of the communication coverage [11, 12]. Each industry contains several transceivers, amplifiers, signal generators and other functional modules (Figure 2).

The following formula allows you to calculate the total electrical energy consumption. (E_{total}) of the BS:

$$E_{total} = n_{sector} \cdot (n_{Tx} \cdot E_{amp.} + E_{trans.} + E_{sig.proc.} + \\ + E_{conv.} + E_{sig.gen.}) + E_{cool.sys.} + E_{micr.link.} \quad \ldots (1)$$

where is:

n_{sector} - Number of sectors in BS;



[Fig.2: Mobile Communication Base Station Energy Consumers]

n_{Tx} _ number of active transceivers in each sector;

$E_{amp.}$ - amplifier power consumption;

$E_{trans.}$ - transceiver power consumption;

$E_{sig.proc.}$ - electrical energy consumption in digital signal processing;

$E_{conv.}$ - power consumption of the AC-DC converter;

$E_{sig.gen.}$ - electrical energy consumption of the signal generator;

$E_{cool.sys.}$ - cooling systems electricity consumption;

$E_{micr.link}$ - microwave communication device power consumption;

By determining the share of each technical component in the energy consumption within these systems, it is possible to identify measures to increase overall efficiency and optimise them accordingly. The analysis results indicate that the cooling system is the most energy-intensive

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component of the base station equipment. It functions to balance the temperature of devices in the TS and prevent overheating, accounting for 36.4% of the total energy consumption. (Table I). Reliable electricity supply is of significant technological and strategic importance in ensuring the functional stability and continuity of service of mobile communication base stations. The main functional blocks contained in the base station - transceivers, signal amplifiers, cooling systems, and control modules -

Table-I: Mobile Communication Base Station Energy Consumers

Component	Energy Consumer Identification	Share in Total Electricity Consumption (%)	Note
Base station	E_{total}	100	General system
Amplifier	$E_{amp.}$	16.1	Amplifies the signal before transmitting it to the antenna
Transceiver	$E_{trans.}$	7.1	Total consumption of transmitting and receiving units
Digital signal processing	$E_{sig.proc.}$	7.3	Encodes and modulates data
AC-DC converter	$E_{conv.}$	7.2	Converts 220V AC to 48V DC
Signal generator	$E_{sig.gen.}$	20.1	Generates frequency and waveform
Cooling system	$E_{cool.sys.}$	36.4	Controls the temperature of the room where the BS devices are located
Microwave communication	$E_{micr.link}$	5.8	Connects BS to the leading network

require constant and stable electrical power. Any disruption in the power supply will result in the cessation of station operations, a decline in the quality of communication services, and the disconnection of network users. Therefore, modern base stations are equipped with not one, but several primary and backup power sources [13].

The primary power source for the base station is the external AC grid. This grid operates at a voltage of 220/380 V and serves as the primary power source for the station's daily operations. It is considered the most suitable source due to its stability and low operating costs. However, network outages due to emergencies, planned maintenance work or natural disasters can negatively affect the operation of the substation. In such situations, the availability of additional energy sources becomes a decisive factor [14, 15].

The most common backup power source is batteries. Typically, Li-ion or lead-acid batteries with a nominal voltage of 48 V are widely used in stations. They automatically continue to supply power in the event of a power outage. Batteries can provide a charge for 30 minutes to 2 hours, making them ideal for medium-term outages. However, constant charging and discharging shortens their lifespan and increases maintenance and repair costs [16].

In recent years, the introduction of supercapacitors in the power architecture of base stations has brought about significant changes. Supercapacitors are devices characterised by high power density, low internal resistance, and the ability to start up in milliseconds, enabling them to quickly compensate for short-term power outages. Their ability to withstand up to 100,000 charge/discharge cycles and environmental friendliness make them an effective backup source. However, their low energy density makes them unsuitable for long-term energy supply. For this reason, supercapacitors are often used in conjunction with batteries in complex systems [17].

Diesel generators play a key role in long-term power outages. As an independent energy source, generators can automatically start up and provide the plant with uninterrupted electricity for several hours or days. Their capacity is selected depending on the load. However, factors such as fuel consumption, operating costs, noise level and negative environmental impact limit the use of generators [16].

Additionally, renewable energy sources, such as solar panels and wind generators, are being introduced at base stations to ensure energy independence and enhance environmental sustainability. Such systems are mainly used in remote areas where there is no electricity grid or frequent outages. Solar panels generate energy through the photovoltaic effect, while wind turbines convert kinetic energy into electricity. Their main advantages are environmental friendliness and low long-term operating costs. However, high initial capital costs and dependence on climatic conditions prevent these sources from becoming a universal [17].

Based on the above analysis, it can be concluded that efficient energy supply for base stations should not rely on a single source, but rather on a complex, automated, and integrated alternative source. Continuity and efficiency can be ensured using optimized control algorithms that take into account the unique advantages and limitations of each source [18].

III. RESULTS AND DISCUSSION

By determining the physical and technological characteristics of the electrical energy sources involved in ensuring the uninterrupted operation of mobile communication base stations, and by building their mathematical models, it is possible to design a general system operation algorithm. Each energy source has its own energy storage or production mechanism, and it is of practical importance to express its dynamics using mathematical equations [19].

Local electricity grid. The external power grid, when considered as an AC source, is modelled by a sinusoidal voltage function. The voltage and current changes with time are expressed as:

$$u(t) = U_G \cdot \sin(\omega \cdot t + \varphi),\ i(t) = = I_G \cdot \sin(\omega \cdot t + \varphi - \theta) \quad \dots \ (2)$$

Here U_{grid} and I_{grid} are the maximum voltage and current amplitudes,

ω - angular frequency;

ϕ - phase step;

θ - power factor phase difference.

The average capacity of the local electricity network is determined as follows:

$$P_{grid} = V_t \cdot I_t \cdot cos(\theta) \quad \dots \ (3)$$

Here, cos(θ) is the power factor;

Accumulator battery. Batteries, which are considered backup sources, are usually represented using a lumped-element RC model. In this model, the output voltage is determined by the open-circuit voltage and internal resistance of the battery:

$$U_b(t) = U_{OC} - I(t) \cdot R_{\text{int}} \quad \dots \ (4)$$

Here U_{oc} is the open circuit voltage, R_{int} is the internal resistance, and $I(t)$ is the load current. The battery's state of charge (SoC) is expressed as:

$$SoC(t) = SoC_0 - \frac{1}{C}\int_0^t I(\tau)d\tau \quad \dots \ (5)$$

where C is the battery capacity (in Ah);

SoC_0 - initial charge level;

Using the above expressions, the mathematical model for charging and discharging a $LiFePo_4$ battery used for BS is as follows. For the discharge process:

$$U_b = E_0 - R \cdot i - K \cdot \frac{Q}{Q - it} \cdot (it + i^*) + A \cdot e^{-B \cdot it} \quad \dots \ (6)$$

For the charging process:

$$U_b = E_0 - R \cdot i - K \cdot \frac{Q}{it - 0.1 \times Q} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + + A \cdot e^{-B \cdot it} \quad \dots \ (7)$$

Supercapacitors, which are used as fast-response backup sources, store energy through an electrostatic field. Their stored energy is a quadratic function of voltage:

$$E_{sc} = \frac{1}{2} \cdot C \cdot U^2 \quad \dots \ (8)$$

Where C is the capacitance (farad),

U is the voltage.

The charge/discharge process is expressed as follows:

$$\frac{du_C}{dt} = \frac{-(u_C)}{(R_{liniya} + R_{EQ})(C_O + 2ku_C)} \quad \dots \ (9)$$

The high power density and fast charge-recharge properties of supercapacitors make them a reliable and efficient temporary energy source for overcoming short-term interruptions and voltage fluctuations in the power supply. In particular, their ability to quickly adapt to fluctuating loads, combined with a significantly higher cyclic endurance compared to conventional battery systems, makes them a crucial technological solution for ensuring the stability of energy infrastructures [20].

Solar panels. The sun is a clean and abundant renewable energy source available worldwide. Solar panels collect solar energy and convert it into electricity. In a solar panel system, modules consisting of many interconnected solar panels, either in series/parallel, are connected to generate energy. The following formula calculates the energy generated by solar panels [17]:

$$E_s = A \cdot \eta_m \cdot P_f \cdot \eta_{PC} \cdot I \quad \dots \ (10)$$

Here, *A* is the total area of the solar cell (m^2),

η_m – module efficiency;

P_f - packing factor;

η_{PC} - power adjustment efficiency (0.86);

I - hourly radiation ($kWt \cdot h / m^2$).

Wind generator. Although wind energy is available throughout the day, unlike solar energy, wind speed is highly variable. There are several methods for calculating the annual energy production of a wind turbine, including the cleared area method, manufacturer estimates, and the power curve method. A wind turbine is characterized by a power curve that shows the power output versus wind speed.

A wind generator system generates energy by converting wind speed into mechanical energy, which is then converted into electrical energy. The kinetic energy of the wind is represented by the power contained in it [17]:

$$P_w = \frac{1}{2} \cdot C_e \cdot \rho \cdot A \cdot v^3 \quad \dots \ (11)$$

were

C_e – generator efficiency coefficient;

A – surface formed by the rotation of the blades;

P – air density;

v – wind speed.

The amount of energy produced by a wind generator is as follows:

$$E_w = P_w \cdot \Delta t \quad \dots \ (12)$$

When developing a mathematical model of the joint operation of supercapacitors and batteries, several key parameters are taken into account. In particular, their voltage, depending on the amount of charge, provides the base station with electrical energy. If these parameters are maintained within the specified limits, providing the base station with electrical energy, the efficiency and service life of the backup energy supply sources will be extended.

Power balance equations for mobile communication BS energy supply:

$$P_{grid} = U_{grid}(t)\cdot I_{grid}(t),\ P_w = U_w(t)\cdot I_w(t),$$
$$P_s = U_s(t)\cdot I_s(t),\ P_{sc} = U_{sc}(t)\cdot I_{sc}(t), \quad \ldots \quad (13)$$
$$P_b = U_b(t)\cdot I_b(t),\ P_d = U_d(t)\cdot I_d(t).$$

If there are no outages in the local power grid and the voltage is within the specified limits:

$$U_{grid} \in \left[U_{grid_{\min}}, U_{grid_{\max}}\right] \Rightarrow$$
$$E_{BS}(t) = P_{grid}\cdot t = U_{grid}(t)\cdot I_{grid}(t)\cdot t \quad \ldots \quad (14)$$

If there is a local power outage or the voltage exceeds the specified limit, and the supercapacitor battery is greater than or equal to the specified minimum limit, then the following will happen:

$$U_{grid} \notin \left[U_{grid_{\min}}, U_{grid_{\max}}\right] \text{ and } U_{sc} \ge U_{sc_{\min}} \Rightarrow$$
$$E_{BS}(t) = P_{sc}\cdot t \quad \ldots \quad (15)$$

If the supercapacitor's voltage drops below the specified minimum limit and the wind generator voltage value is greater than or equal to the specified minimum limit:

$$U_{sc} < U_{sc_{\min}} \text{ and } U_w \ge U_{w_{\min}} \Rightarrow E_{BS}(t) =$$
$$= P_w\cdot t = \frac{1}{2}\cdot C_e\cdot \rho\cdot A\cdot v^3\cdot t. \quad \ldots \quad (16)$$

If the voltage value produced by the wind generator falls below the specified minimum threshold, and the solar panels are greater than or equal to the specified minimum threshold:

$$U_w < U_{w_{\min}} \text{ and } U_s \ge U_{s_{\min}} \Rightarrow E_{BS}(t) =$$
$$= P_s\cdot t = A\cdot \eta_m\cdot P_f\cdot \eta_{PC}\cdot I \quad \ldots \quad (17)$$

If the voltage value generated by the solar panels falls below the specified minimum limit and the battery voltage is greater than or equal to the specified minimum limit, then the following will happen:

$$U_s < U_{s_{\min}} \text{ and } U_b \ge U_{b_{\min}} \Rightarrow E_{BS}(t) = P_b\cdot t =$$
$$= (E_0 - R\cdot i - K\cdot \frac{Q}{Q-it}\cdot (it + i^*) + A\cdot e^{-B\cdot it})\cdot i(t) \quad \ldots \quad (18)$$

If the battery voltage drops below the minimum threshold and the diesel generator is started, the following will happen:

$$U_b < U_{b_{\min}} \text{ and } U_d \ge U_{d_{\min}} \Rightarrow E_{BS}(t) = P_d\cdot t =$$
$$U_d(t)\cdot I_d(t)\cdot \bar{e}_d \quad \ldots \quad (19)$$

The mathematical model describing the process of managing energy supply sources in this system, taking into account various conditions, looks like this:

$$E_{BS} = \begin{cases} E_{grid} \ \text{if} \ U_{grid} \in \left[U_{grid_{\min}}, U_{grid_{\max}}\right]; \\ E_{sc} \ \text{if} \ \begin{cases} U_{grid} \notin \left[U_{grid_{\min}}, U_{grid_{\max}}\right], \\ U_{sc} \ge U_{sc_{\min}}; \end{cases} \\ E_w \ \text{if} \ \begin{cases} U_{sc} < U_{sc_{\min}}, \\ U_w \ge U_{w_{\min}}; \end{cases} \\ E_s \ \text{if} \ \begin{cases} U_w < U_{w_{\min}}, \\ U_s \ge U_{s_{\min}}; \end{cases} \\ E_b \ \text{if} \ \begin{cases} U_s < U_{s_{\min}}, \\ U_b \ge U_{b_{\min}}; \end{cases} \\ E_d \ \text{if} \ \begin{cases} U_b < U_{b_{\min}}, \\ U_d \ge U_{d_{\min}}; \end{cases} \\ 0 \ \text{if} \ U_{DG} < U_{DG_{\min}}; \end{cases} \quad \ldots \quad (20)$$

where

E_{BS} - base station load;

E_{grid}, U_{grid}, $U_{grid_{\min}}$, $U_{grid_{\max}}$ - local power grid parameters;

E_{sc}, U_{sc}, $U_{sc_{\min}}$ - supercapacitor battery parameters;

E_w, U_w, $U_{w_{\min}}$ - wind generator parameters;

E_s, U_s, $U_{s_{\min}}$ - solar panel parameters;

E_b, U_b, $U_{b_{\min}}$ - battery parameters;

E_d, U_d, $U_{d_{\min}}$ - diesel generator parameters;

IV. RESULTS

To effectively manage the power system of mobile communication base stations, it is necessary to develop an efficient monitoring and automatic control system for energy supply sources. There are various circuits and microcontrollers for system development, including TINA-TI, Multisim, Proteus, LTspice, KiCad, Altium Designer, MATLAB/Simulink, PSCAD, PSpice, ETAP, and Power World Simulator, among other programs for simulation based on the developed mathematical model [21].

Among the above programs, the Proteus program enables the selection of network elements, writing of software codes, and building of a simulation model of the system during the modelling process. With the help of this program, it is possible to create a model of the system, check the operation process, design electronic circuits and carry out diagnostics on them. Proteus is a program belonging to the category of VSM (Virtual Simulation Modelling), which allows not only the schematic development of electronic systems but also the real-time analysis of their operational principles. Therefore, this program is widely used in modelling microprocessor-based devices, power supply systems, and automation systems.

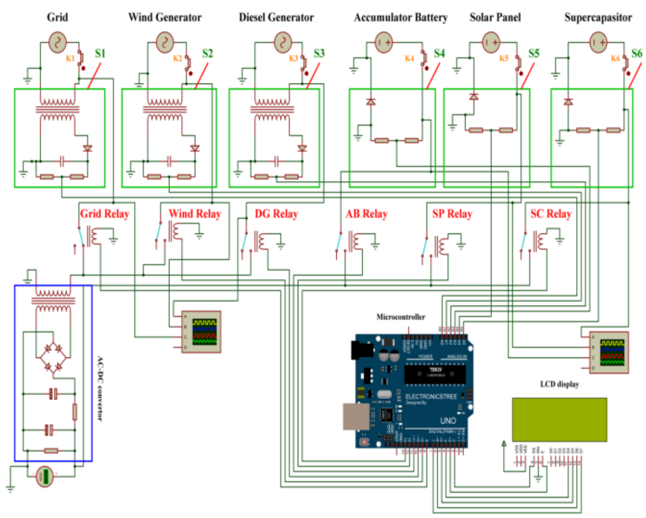
According to current methods of managing energy supply sources, batteries or diesel generators are used as backup energy sources in the event of a power outage.

Although these methods are effective, they have certain disadvantages. In particular, the number of charges/discharges of batteries is limited, and the service life is reduced in case of repeated short-term interruptions. Additionally, it cannot quickly respond to interruptions. Diesel generators have high operating costs, require a constant supply of fuel and are environmentally harmful.

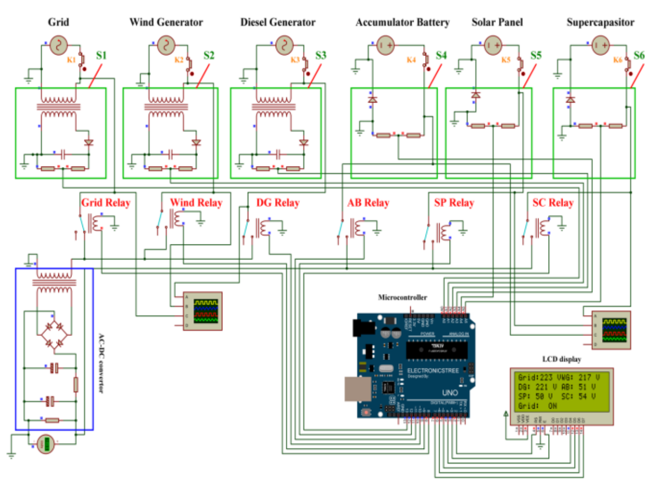
Supercapacitors play a crucial role in optimising the energy supply system of mobile communication base stations. Supercapacitors have high power density and rapid charging and discharging, which allows for adequate compensation of short-term power outages. It is for this reason that we offer supercapacitors as a primary backup source in the event of mains power outages.

(20) - Based on the mathematical model in the expression, the power supply management system of mobile communication base stations and its operating processes were modelled using the Proteus Professional 8.17 SP4 program (Figure 3). Local power grids, wind generators, diesel generators, storage batteries, solar panels, and supercapacitor batteries were used as sources of electricity to provide continuous power to the mobile communication base station. K1, K2, K3, K4, K5, and K6 switches are used to control the availability of sources. Transformers, diodes, capacitors, and parallel resistors are used for variable power supply sources, while diodes and parallel resistors are used for constant power supply sources. Relay modules controlled via a microcontroller have been employed to connect and disconnect power supply sources to the load. An Arduino UNO microcontroller was used to control the relay modules and continuously monitor the power supply sources, while an LCD was employed to observe system status information. In the simulation model, the AC-DC converter converts the alternating voltage coming from the local power grid, wind generator, and diesel generator into a stable 48 V DC voltage suitable for the base station load.

This statement means that if there is no interruption in the local power grid and the voltage is within the specified limits, the local power grid supplies electricity to the base station (Figure 4). Suppose the voltage in the local power grids exceeds the specified limit or there is an interruption in the local grids, and the supercapacitors are above the specified minimum threshold. In that case, the supercapacitors supply electricity to the base station (Figure 5). If the supercapacitors drop below the specified minimum threshold and the wind generator's voltage is above the specified minimum threshold, then the wind generator supplies electricity to the base station (Figure 6). Suppose the wind generator's voltage is below the specified minimum threshold, and the voltage of the solar panels is above the specified minimum threshold. In that case, the solar panels supply electricity to the base station (Figure 7). During the supply of electricity from the solar panels, their voltage is continuously monitored. If this parameter drops below the specified minimum threshold, the batteries supply electricity to the base station (Figure 8). During the power supply from the batteries, their voltage is also continuously monitored. Suppose the voltage drops below the specified threshold, and the local power grids have not been restored. In that case, then an uninterrupted power supply to the base station is provided by the diesel generator (Figure 9). The voltage output of the diesel generator is also continuously monitored, and if it drops below the specified threshold, a power outage occurs at the base station (Figure 10). The electrical parameters generated by the power supply sources were examined using a digital oscilloscope. Figure 11 illustrates the variation of electrical parameters when power is obtained from the local grid, wind generator, and diesel generator. In contrast, Figure 12 shows the variation of electrical parameters when power is sourced from the battery, solar panels, and supercapacitors.



[Fig.3: The Initial State of the Management System of Electric Energy Supply Sources]



[Fig.4: The Main Power Supply Source Parameter is within the Specified Limits]

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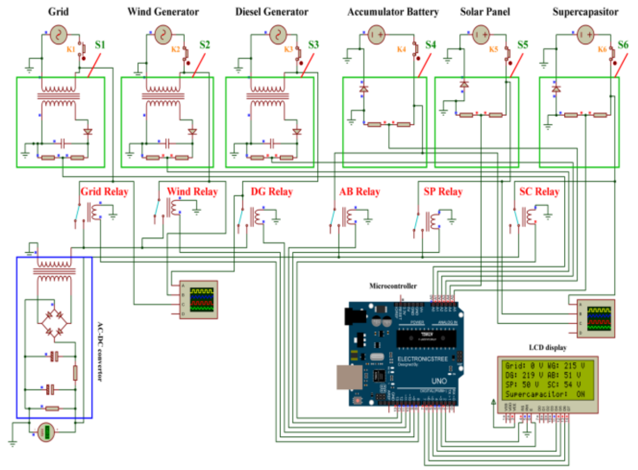
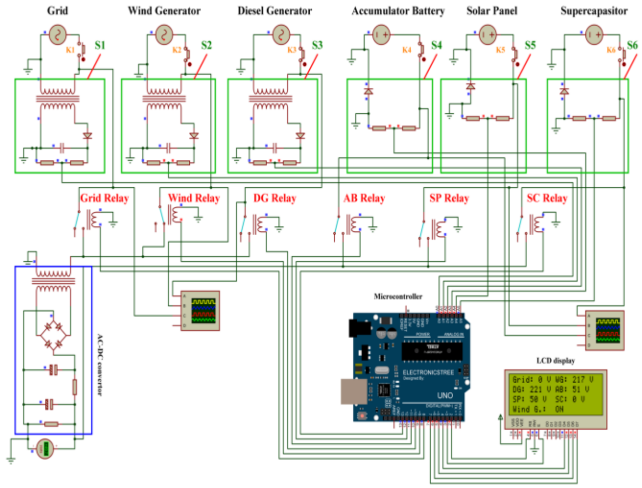
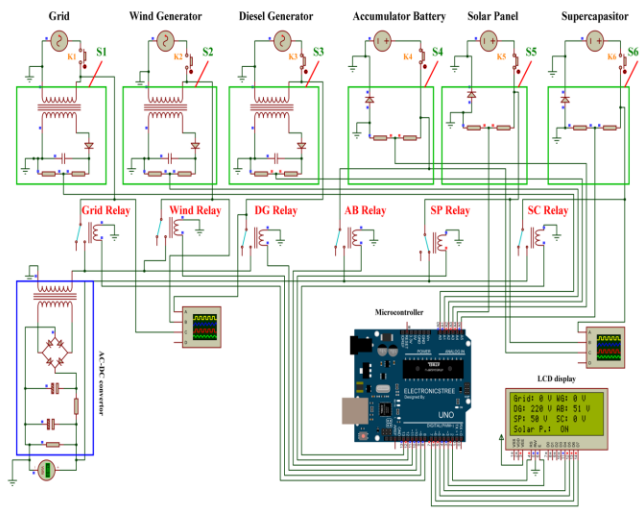


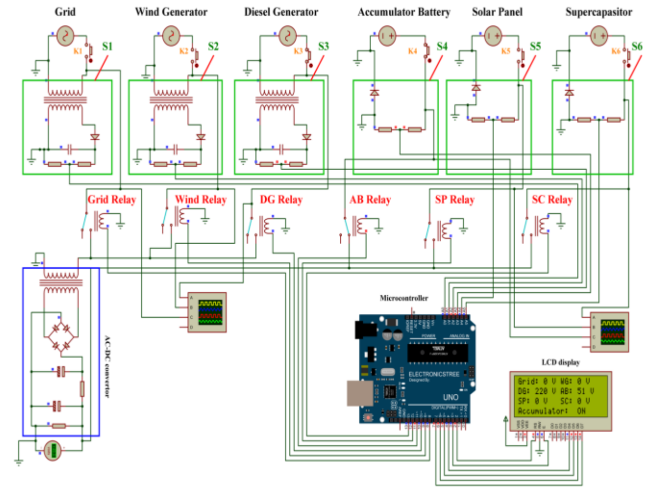
[Fig.5: A Situation Where There is an Interruption in the Primary Source of Electricity Supply, and the Supercapacitor Parameter is within the Specified Limits]



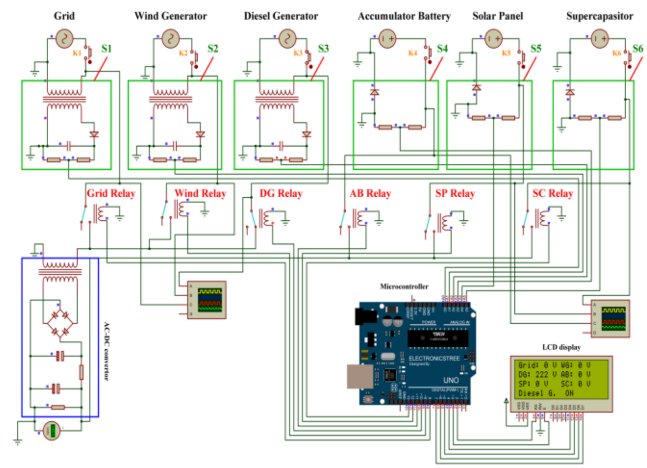
[Fig.6: A Condition in Which the Supercapacitor Bank Experienced a Disruption, and the wind Generator Operated Within the Defined Parameter Limits]



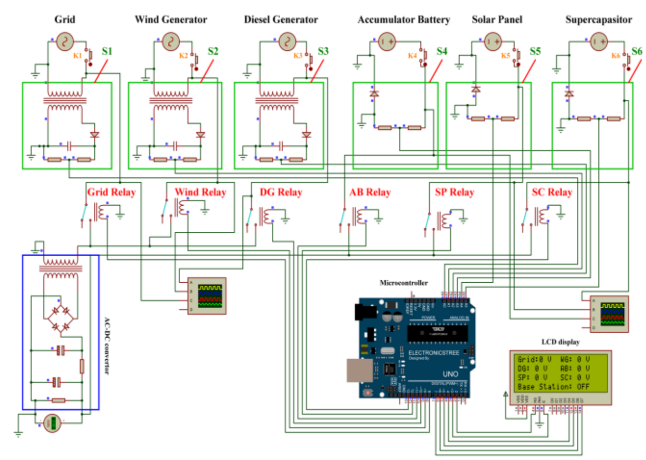
[Fig.7: A Case Where the Wind Generator has an Outage and the Solar Panel Parameter is Within Limits]



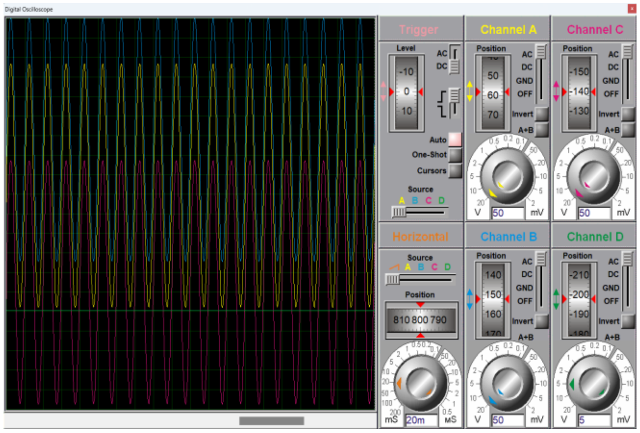
[Fig.8: A Situation Where There is an Interruption in the Solar Panels and the Battery Parameter is Within the Specified Limits]



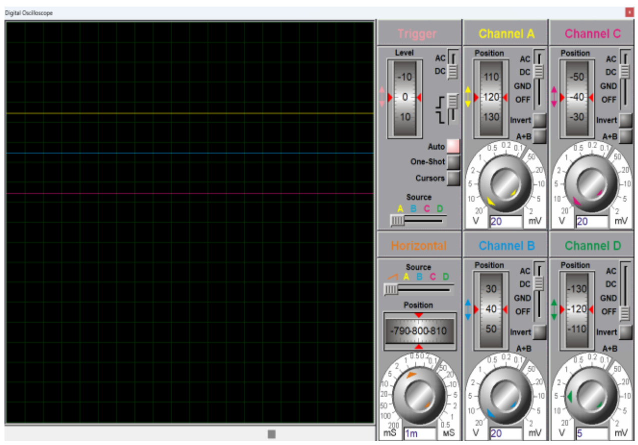
[Fig.9: A Condition in Which the Battery Experienced a Disruption, and the Diesel Generator Operated Within the Specified Parameter Limits]



[Fig.10: A Situation Where all Electricity Supply Sources are out of Order]



[Fig.11: The Graph of Changes in Electrical Quantities when Receiving Electricity from Local Power Grids, a Wind Generator, and a Diesel Generator]



[Fig.12: The Graph of Changes in Electrical Quantities when Obtaining Electrical Energy from Batteries, Solar Panels and Supercapacitors]

To ensure an uninterrupted power supply to the base station, integrating supercapacitors into the electrical power system is recommended. Due to the rapid response capability of supercapacitors during power interruptions, peak power consumption can be reduced, potentially improving overall energy efficiency by 4–5%. Additionally, supercapacitors can reduce the response time to initial disturbances in the power supply by up to 10 times. This approach helps prevent potential power interruptions in base station operations, thereby enhancing the overall system stability. Furthermore, implementing supercapacitors can increase the operational efficiency of the base station by approximately 1.5–2%.

V. CONCLUSIONS

To ensure an uninterrupted and reliable power supply for mobile communication base stations, a mathematical model was developed that comprehensively considers the operating modes of various energy sources, including the local power grid, solar panels, wind generators, supercapacitors, batteries, and diesel generators. This model enables the mathematical representation of energy supply scenarios that occur under real operating conditions, the analysis of system stability in various situations, and the modelling of the interaction between energy sources. The proposed mathematical model enabled the simulation of an algorithm for effective energy resource management and real-time system operation. Using the Proteus software, a simulation model of an uninterrupted power supply system for mobile communication base stations was developed. Based on this model, experimental tests were conducted. The results of these tests demonstrated that the model is capable of providing a rapid response to power interruptions in the base stations, depending on the status of the energy sources, thereby ensuring an uninterrupted power supply. It was also found that utilizing supercapacitors as a primary power source during interruptions reduced the response time by a factor of 10.

DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

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