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AC Bio-Inspired Micro-Grid Architecture for Renewable-Rich Urban Distribution Systems

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ABSTRACT: As cities move rapidly toward high levels of renewable energy, the weaknesses of traditional urban AC distribution networks are becoming hard to ignore. These systems were originally designed for large, centralized power plants and long-distance transmission [9], [10]. Today, they must handle rooftop solar, distributed wind, bidirectional power flow, and rising demand [1], [2]. The result is higher copper losses, repeated voltage conversions, reactive power circulation, and inefficient AC–DC–AC stages. Simply upgrading existing components is no longer enough the structure of the grid itself needs to evolve. This paper proposes a new approach: An AC Bio-Inspired Micro-Grid (BIMG) architecture modeled after the ventilation and transport networks of plant leaves. In a leaf, energy and nutrients are distributed through a finely branched structure that minimizes transport distance while maintaining uniform supply and resilience [7], [8]. There is no single distant control point; instead, regulation happens locally and efficiently across the network. Applying this principle to power systems, the proposed architecture localizes renewable generation near load centers, aggregates distributed sources through a DC layer, and uses grid-forming invert to Synthesize stable medium-voltage AC [3], [4]. Instead of behaving like a rigid radial system, the network operates more like a living structure decentralized, adaptive, and efficient. A first-principle analytical loss model based on three-phase power flow equations is developed to compare the proposed system with a conventional urban network. For a 70 MW case study, the traditional architecture shows total system losses of approximately 19.6%, while the bio-inspired MG reduces losses to 6.27% nearly a 68% reduction. These improvements come from shorter electrical paths, better power factor control, and fewer conversion stages.

1. Introduction

The main principle of the AC BIMG comes from observing how a leaf works in nature [7]. In a leaf, energy and nutrients are distributed through many small, branched pathways instead of one long central channel. This reduces resistance and makes the system efficient and balanced [8]. Similarly, this MG generates electricity close to where it is consumed, rather than sending it over long distances from a faraway power plant [1], [2]. By reducing electrical distance, improving power factor, and minimizing unnecessary conversion stages, the system lowers energy losses and improves stability. In simple terms, the principle is: shorter paths, local control, and smarter energy flow mean less waste and better performance [9], [10].

Construction of a Layered Urban Renewable Energy Distribution System:

The construction of this system is layered and organized. First, renewable sources like rooftop solar panels and small wind turbines are installed near buildings and load centers. These sources mainly produce DC power, which is collected through a common DC aggregation layer [4], [6]. This DC layer helps combine and stabilize the power from different renewable sources. After that, grid-forming inverters convert DC power into stable AC power with controlled voltage and frequency. Finally, this AC power is distributed through existing urban feeders to homes, offices, and industries. The overall structure is simple: local generation, DC collection, intelligent conversion, and short-distance distribution [3], [11].

2. Working of Urban Renewable Energy Distribution System

In operation, renewable sources generate electricity throughout the city during the day. The power flows into the DC bus, where variations from solar or wind are managed smoothly [4], [6]. Grid-forming inverters then convert this power into AC and regulate voltage and frequency automatically depending on load demand [6], [11]. If demand increases, the inverters supply more power; if demand decreases, they reduce output. Since electricity is produced and used locally, it travels shorter distances, which reduces line losses. The system can also connect to the main utility grid when needed or operate independently during faults. Overall, it works like a living energy network adapting, balancing, and distributing power efficiently within the city [9], [10].

Why Do Modern Grids Need Decentralization?

Earlier power systems were built around large power plants located far from cities. Electricity flowed in one direction from the plant to the consumer, and this worked well when demand was steady and predictable [9].

Today, the situation has changed. Cities are growing, rooftop solar and wind systems are increasing, and power now flows in multiple directions. In traditional grids, long transmission distances cause higher energy losses, voltage drops, and larger outages when failures occur [5], [1]. Decentralization solves this by generating power closer to where it is used. This reduces losses, improves voltage control, and increases reliability [11]. The AC BIMG follows this idea, creating a more efficient and resilient system suited for modern urban needs [3].

3. Structure of the AC inspired MG

The structure of the AC BIMG is fully based on the renewable energy. First, renewable sources like rooftop solar panel, hydro power, biogas, geothermal, wind turbines are installed near buildings and load centers. There are 10 total feeders in the system for example each carries 7MW. The power is produced locally and consumed locally. In the absence of the renewable energy the non-renewable power generations are only used in critical situations.

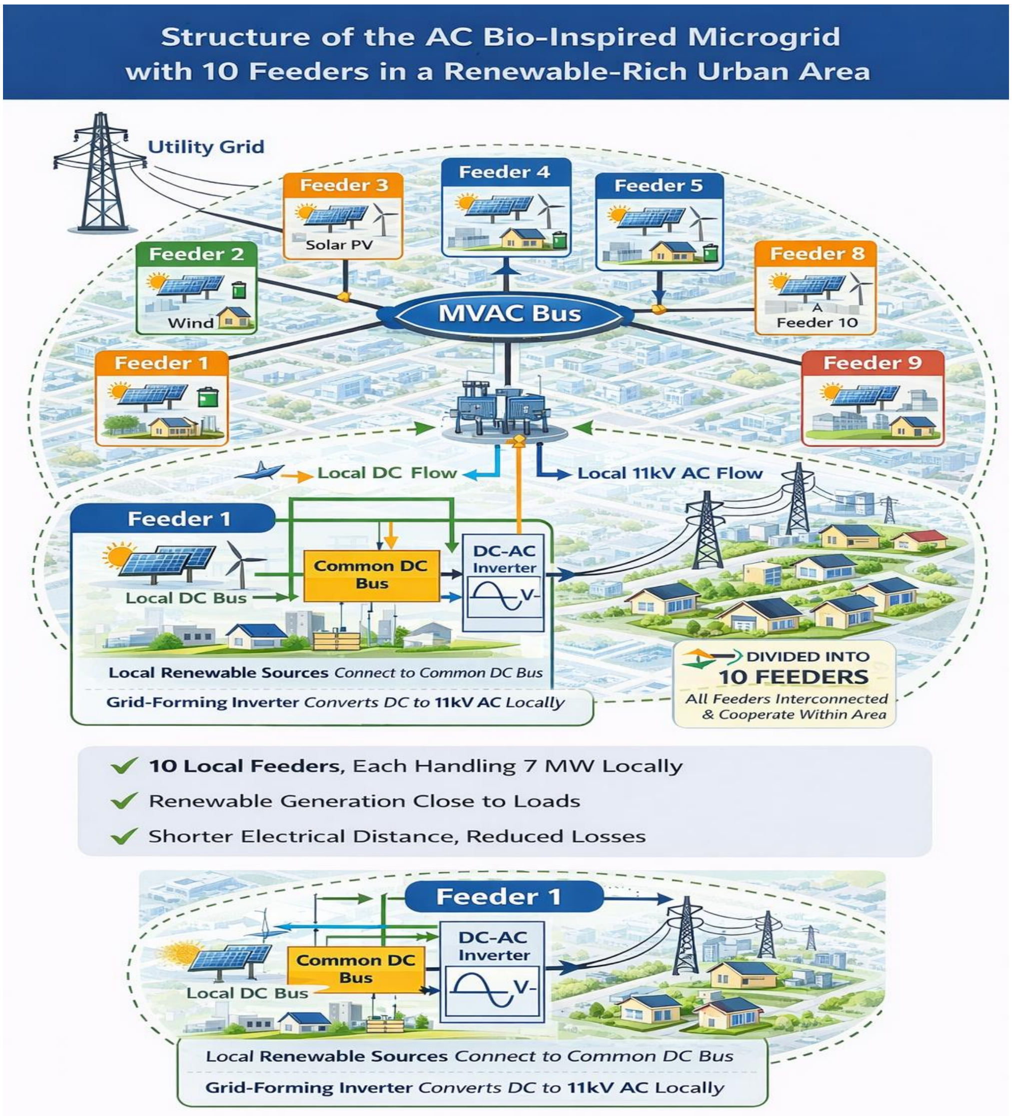


Figure 1: *Structure of the AC BIMG*

4. Mathematical Derivation of Distribution Losses

ASSUMPTIONS (Realistic Distribution Level) [9],[10], [4],[11].

Total Load = 70 MW

Voltage Level = 11 kV

Power Factor:

Urban grid = 0.92

Bio-grid = 0.98

Number of feeders = 10

Each feeder carries = 7 MW

Conductor resistance = 0.2 Ω/km

Urban feeder length = 8 km
Bio-grid feeder length = 3 km

Operating hours per year = 8760 h

Urban Grid

Line Resistance per feeder:

$$R = r \times L \ldots \qquad (1)$$

$$R = 0.2 \times 8 = 1.6\ \Omega$$

Current per feeder:

$$I = \frac{P}{\sqrt{3}v_L \cos \emptyset} \ldots \qquad (2)$$

$$I = \frac{7 \times 10^6}{\sqrt{3} \times 11000 \times 0.92}$$

$$I = 399.6\ \text{A}$$

Line Loss per feeder:

$$P_{loss} = 3I^2R\ldots \qquad (3)$$

$$P_{loss,f} = 3(399.6)^2 \times 1.6$$

$$P_{loss,f} = 0.767 \text{ MW}$$

For 10 feeders:

$$P_{loss,line} = 7.67 \text{ MW}$$

Transformer Loss:

Two stages (33/11 kV and 11/0.415 kV) Typical efficiency per stage = 98%

$$\eta = 0.98^2 = 0.9604$$

$$P_{loss,trans} = Pin(1-\eta)\ \ldots \qquad (4)$$

$$P_{loss,trans} = 70(1-0.9604)$$

$$P_{loss,trans} = 2.77 \text{ MW}$$

Converter Loss (60% renewable):

Two stages at 96% each:

$$P_{loss,conv} = 0.6 \times 70 \times (1-0.9216)$$

$$P_{loss,conv} = 3.29 \text{ MW}$$

Total Urban Grid Loss:

$$Loss\% = \frac{P,loss}{P,load} \times 100\ldots \qquad (5)$$

$$Loss\% = \frac{13.73}{70} \times 100 = 19.6\%$$

Annual Energy Loss

$$\text{E=P,loss×8760}\ldots \qquad (6)$$

$$E_{urban} = 13.73 \times 8760$$

$$E_{urban} = 120{,}275 \text{ MWh/year}$$

AC BIMG

- Feeder length reduced to 3 km
- PF improved to 0.98
- One transformer stage
- One conversion stage

Resistance:

$$R = r \times L\ldots \qquad (1)$$

$$R = 0.2 \times 3 = 0.6\ \Omega$$

Current:

$$I = \frac{P}{\sqrt{3}v_L \cos \emptyset}\ldots \qquad (2)$$

$$I = \frac{7 \times 10^6}{\sqrt{3} \times 11000 \times 0.98}$$

$$I = 372.8 \text{ A}$$

Line Loss per feeder:

$$P_{loss} = 3I^2R\ldots \qquad (3)$$

$$P_{loss,f} = 3(372.8)^2 \times 0.6$$

$$P_{loss,f} = 0.25 \text{ MW}$$

For 10 feeders:

$$P_{loss,line} = 2.5 \text{ MW}$$

Transformer Loss (Single stage 98.5%):

$$P_{loss,trans} = Pin(1-\eta)\ \ldots \qquad (4)$$

$$P_{loss,trans} = 70(1-0.985)$$

$$P_{loss,trans} = 1.05 \text{ MW}$$

Converter Loss (Single stage 98%):

$$P_{loss,conv} = 0.6 \times 70 \times 0.02$$

$$P_{loss,conv} = 0.84 \text{ MW}$$

Total Bio-Grid Loss:

$$Loss\% = \frac{P,loss}{P,load} \times 100\ldots \qquad (5)$$

$$P_{total,bio} = 4.39 \text{ MW}$$

$$Loss\% = \frac{4.39}{70} \times 100 = 6.27\%$$

Annual Energy Loss:

$$\text{E=P,loss×8760}\ldots \qquad (6)$$

$$E_{bio} = 4.39 \times 8760$$

$$E_{bio} = 38{,}456 \text{ MWh/year}$$

Parameter	Urban Grid	Bio Grid
Line Loss	7.67 MW	2.5 MW
Transformer	2.77 MW	1.05 MW
Converter	3.29 MW	0.84 MW
Total Loss	13.73 MW	4.39 MW
Loss %	19.6%	6.27%

Table 1: *Comparison of Annual Energy for Urban Grid and Bio Grid*

Table 1 compares the annual energy losses of the Urban Grid and the Bio Grid systems. The Urban Grid shows higher losses in the line (7.67 MW), transformer (2.77 MW), and converter (3.29 MW), leading to a total loss of 13.73 MW (19.6%). In contrast, the Bio Grid significantly reduces losses in all components, with line losses of 2.5 MW, transformer losses of 1.05 MW, and converter losses of 0.84 MW, resulting in a total loss of only 4.39 MW (6.27%). Overall, the Bio Grid demonstrates better energy efficiency and improved system performance by effectively minimizing transmission and conversion losses. Urban grid:

120,275MWh/year

Bio-grid:

Savings= E,saved×Cost per kWh

4.39 × 8760 = 38,456 MWh/year

Annual Energy Saved

120,275−38,450

=81,819 MWh/year

At ₹6 per kWh:

Savings=81,819,000×6

=₹49.09 Crores/year

Advantages of AC BIMG

The BIMG model provides several clear technical benefits compared to a traditional urban grid system. With shorter distribution paths and better power factor control, the current flowing through the lines is reduced, which in turn lowers I^2R losses and brings down overall system losses from nearly 19–20% to around 6–7%. The use of local grid-forming inverters further strengthens system performance by maintaining stable voltage, supporting reactive power, regulating frequency, and reducing harmonics, ensuring active and dynamic power quality management [4], [6], [11]. Its semi-independent feeder design enhances reliability, as critical loads can continue to operate and islanded mode becomes feasible during main grid failures. The branching, nature-inspired layout also allows flexible expansion and easy integration of renewable sources, making it highly suitable for future-ready and smart urban infrastructure. Moreover, consuming power closer to the point of generation reduces curtailment, conversion losses, and network congestion, thereby improving the effective utilization of renewable energy resources [5].

Limitations of AC BIMG

Even though the BIMG offers many technical benefits, it does come with some practical challenges. One of the main concerns is the higher initial investment needed for components such as grid-forming inverters, energy storage systems, advanced protection equipment, and communication networks, despite the promise of long-term cost savings. Protection design becomes more complicated because power can flow in both directions and inverter-based systems behave differently during faults [11], [12]. Coordinating multiple distributed controllers is also essential to maintain stable voltage, synchronized frequency, and balanced load sharing. In addition, many existing regulations and tariff policies are still structured around centralized generation and need to be revised to effectively support MG operations.

4. Result and Discussion

The analytical and MATLAB-based evaluation of the proposed AC BIMG demonstrates a substantial improvement in distribution efficiency compared to the conventional urban grid architecture. For the 70 MW case study at 11 kV, the traditional urban grid exhibits total system losses of 13.73 MW, corresponding to 19.6% of total load demand [1],[2]. In contrast, the proposed bio-inspired architecture reduces total losses to 4.39 MW, equivalent to 6.27%, resulting in nearly a 68% reduction in overall system losses. Overall, the AC BIMG demonstrates enhanced efficiency, superior voltage regulation, improved renewable utilization, and stronger operational resilience. Although the architecture requires higher initial investment and more advanced protection coordination, the long-term technical and economic benefits strongly support its adoption for renewable-rich urban distribution networks [4],[6].

Table 2 is Comparing the AC BIMG to the traditional urban grid system reveals a number of benefits. By drastically lowering distribution losses (by about 6–7%), it raises total efficiency. It guarantees improved power quality and system stability through active local voltage and power regulation. Because of the MG's improved resilience, it can continue to function even in the event of grid failures or disruptions. Because of its high scalability, adding more renewable energy sources is simple. Additionally, because it uses more clean energy and generates locally, it has less of an influence on the environment.

Feature	**Urban Grid**	**AC Bio-Inspired MG**
Distribution Losses	High (~19–20%)	Low (~6–7%)
Voltage/Power Quality	Passive	Active local control
Resilience	Weak	Strong
Scalability	Limited	High
Environmental Impact	Moderate	Low
Initial Cost	Lower	Higher
Protection Complexity	Standard	Advanced

Table 2. *Features comparison for Urban Grid and AC BIMG*

These elements add to increased dependability, more intelligent operation, and long-term sustainability, despite the initial expense and protection system being more sophisticated.

MATLAB Analysis of Urban Grid and AC BIMG

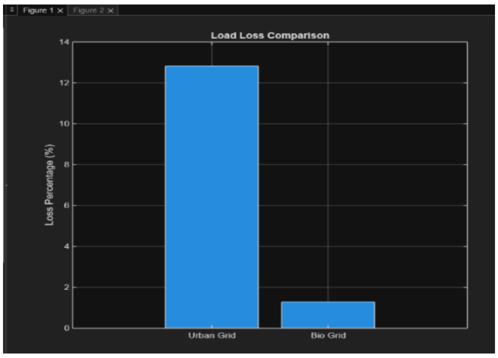


Figure 2: *Load Losses comparison of Urban Grid and AC BIMG*

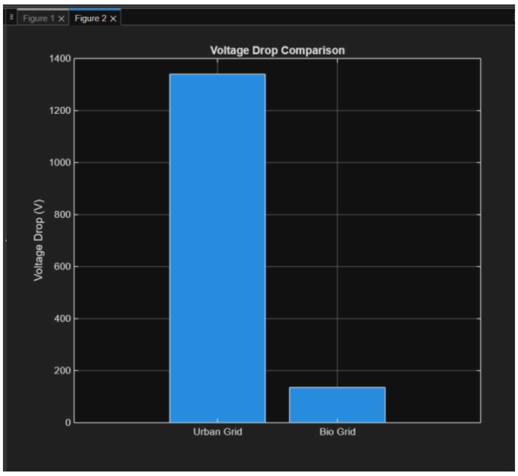
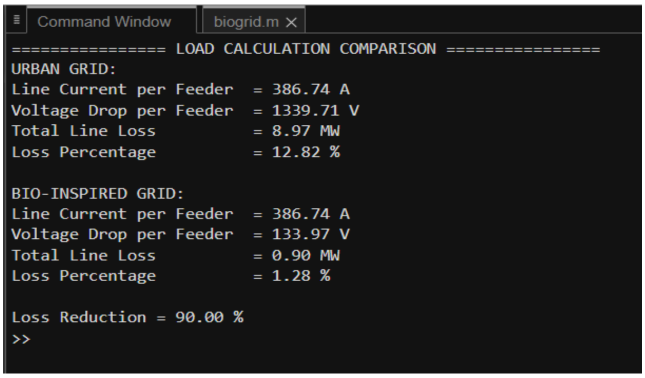


Figure 3: *Voltage drop comparison of Urban Grid and AC BIMG*



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=============== LOAD CALCULATION COMPARISON ===============
URBAN GRID:
Line Current per Feeder   = 386.74 A
Voltage Drop per Feeder   = 1339.71 V
Total Line Loss           = 8.97 MW
Loss Percentage           = 12.82 %

BIO-INSPIRED GRID:
Line Current per Feeder   = 386.74 A
Voltage Drop per Feeder   = 133.97 V
Total Line Loss           = 0.90 MW
Loss Percentage           = 1.28 %

Loss Reduction = 90.00 %
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Figure 4: *Load calculation comparison of Urban Grid and AC BIMG*

5. Conclusion

It is clearly demonstrated that the proposed AC BIMG outperforms the conventional urban grid in terms of efficiency and voltage regulation. The urban grid exhibits a voltage drop of 1339.71 V, total line loss of 8.97 MW, and a loss percentage of 12.82%. In contrast, the BIMG reduces the voltage drop to 133.97 V and the total line loss to

0.90 MW, with the loss percentage decreasing to 1.28%, while maintaining the same feeder current of 386.74 A. This represents an overall loss reduction of approximately 90**%**. Therefore, the proposed AC BIMG significantly enhances power quality, minimizes transmission losses, and improves overall system performance, making it a more efficient and reliable alternative to the conventional urban grid.

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