ASSESSMENT OF TECHNICAL LOSSES IN THE GENERATION AND 330KV TRANSMISSION NETWORK OF NIGERIA'S NATIONAL ELECTRIC POWER SYSTEM

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ABSTRACT

This study focuses on estimating technical losses in the generation system and 330kV transmission network of Nigeria's Electric Power System. The B-coefficient method, which represents transmission losses as a function of the total power output from all generating plants, was applied, while Kron's formula was used for transmission loss estimation. Generation losses were determined by calculating the difference between the fuel input cost ($/h) and the power output (MW) of the generators. Hydrological unit data and thermal cost data were utilized for generation loss assessment. The recorded transmission loss was 5.424 per unit (542.4 MW), while generation losses totaled 25,411.62 MW, resulting in a net technical loss of 25,953.99 MW. To minimize real power losses and enhance system stability, loss-contributing factors should be addressed, and network loops should be established to improve operational flexibility. To minimize Nigeria's 25,953.99 MW technical losses, outdated infrastructure and inefficient operations must be addressed. Establishing network loops and adopting advanced monitoring and optimization tools will enhance system efficiency and stability.

Keywords: Power losses; Generation system; Transmission network; Hydropower; Thermal energy

1 INTRODUCTION

Electrical power serves as the backbone of economic development for most societies and nations. The electricity generated at power stations must be efficiently transmitted to end users through transmission and distribution networks. A key indicator of a nation's development is its per capita electricity consumption [1]. In Nigeria, this index stands at just 14W per person, which is significantly lower compared to other countries [2]. Table 1 presents a comparative analysis of per capita electricity consumption in selected nations, based on data from the International Energy Institute [2]. The economic growth of any country is closely tied to the quality and availability of its electric power supply. In Nigeria, electricity services are often inadequate, unreliable, and inaccessible [3]. The Nigerian power system faces numerous challenges, including instability, insufficiency, and frequent disruptions, making it difficult for consumers to access a steady electricity supply. As a result, the high cost of doing business has negatively impacted the economy, contributing to widespread poverty [4]. Over the years, various Nigerian administrations have promised improvements in electricity supply. However, despite these assurances, significant progress has yet to be achieved due to planning and operational challenges. One major issue is the lack of accurate information regarding power losses within the system, highlighting the need for a comprehensive loss estimation. [4]. Nigeria's power system primarily relies on hydrothermal and gas plants and is characterized by long, fragile, and radial transmission lines. Like any other power network, it experiences energy losses, which include wasted energy at the generation stage or energy transmitted but not effectively delivered to consumers. Generation losses refer to energy produced but not transmitted to load centers, such as heat losses in generator armatures. Transmission losses, on the other hand, occur when energy is transmitted from power plants but cannot be distributed or converted into revenue. Several studies have analyzed power losses in Nigeria's electrical system, particularly in the 330kV network [5, 6, 7, 8]. However, these studies have not considered transmission losses as a function of generator output, a gap this research aims to address. System efficiency is directly linked to reliability, security, and the quality of power delivered to consumers in the right quantity and at the right time. The Nigerian power system is currently in a critical state, and estimating losses will help engineers assess its efficiency. This study seeks to estimate power losses using a more recent system analysis and a more precise methodology, including losses in both the generation and transmission subsystems. The primary objective of this research is to quantify power losses in the generation system and the 330kV transmission network of the Nigeria National Electric Power System (NNEPS). Kron's loss formula is applied to determine transmission losses, while the power differential approach is used for generation loss estimation. [5, 6]. The specific goals of this study include; determining Kron's loss coefficients (B_{ij}, B_{io}, and B_{oo}) to compute losses in the transmission and generation subsystems, analyzing the Nigerian power system to estimate technical losses and providing insights that will help industry stakeholders develop strategies to minimize losses and enhance system performance, ultimately supporting economic growth. [7, 8].

Table 1. Per Capita Electricity Consumption of Selected Countries [1]

Country	Per Capita Consumption per Person (in Watts)
United States of America	1,377
Cuba	68
United Kingdom	547
Ukraine	369
Iraq	125
South Korea	1,109
Nigeria	14
Egypt	172
Ghana	39
Libya	162

2 LITERATURE REVIEW

A study conducted by [9] estimated technical losses in Nigeria's 330kV transmission network, concluding that losses in the transmission and distribution systems accounted for 44.5% of the total power generated and sent out. Of this, 9.2% was attributed solely to transmission lines. However, this study did not address losses within the generation system. According to Gupta et al, electrical losses include field loss, armature winding loss, and brush contact loss. Copper loss in the field circuit can be determined by summing the I2RI^2R loss in the field winding and the electrical loss in the field rheostat or by multiplying the excitation voltage by the field current [10]. Furthermore, Gupta et al, explains that eddy current and hysteresis losses result from the flux interactions between the rotor and stator fields. These losses occur in the armature teeth, core, and pole faces. While core losses remain independent of load, they increase with excitation. If excitation varies with load and power factor changes, core losses also fluctuate. This loss is equivalent to the power required to operate the alternator, regardless of whether the field is excited. Additional losses include friction and winding losses between bearings and brushes. Moreover, space charges produced by the electric field move around the conductor, drawing energy from the supply system. This surrounding space is susceptible to energy losses [11]. The differential power loss approach defines generation losses as the difference between the total power input into the generation system and the power ultimately sent out. This accounts for losses occurring within generators [12].

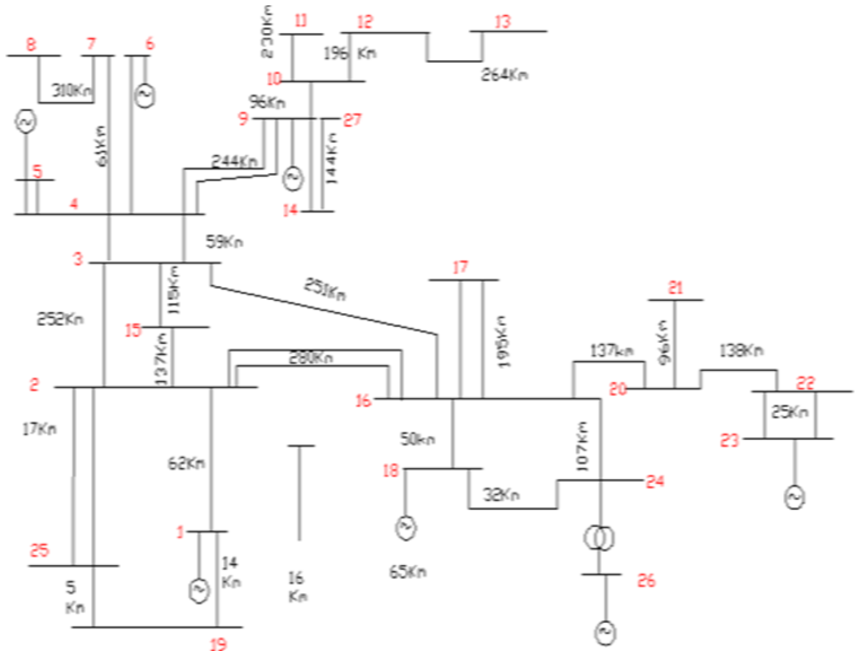

Figure 1. Single Line Diagram with Buses Numbered [12]

2.1 Thermal cost Data

The early commissioned thermal plants in Nigeria, Egbin ST2-5, Delta, Afam IV-V and Sapele (Steam) thermal plants have fully developed cost data. The cost characteristics are given in equations (1) to (4).

$$F_1 = 12787 + 13.1P_1 + 0.031P_1^2 \ \$/hr \quad (1)$$

$$F2 = 525.74 - 6.13P2 + 1.2P_2^2 \ \$/\text{hr} \quad (2)$$

$$F3 = 1998 + 56P3 + 0.092P_3^2 \ \$/\text{hr} \quad (3)$$

$$F4 = 6929 + 7.84P4 + 0.13P_4^2 \ \$/\text{hr} \quad (4)$$

2.2 Hydro-generating unit data

The hydro-generation unit data is shown in Table 2.

Table 2. The Hydro–generating Unit Data [13]

Power Stations Parameters	Kainji	Jebba	Shiroro
Head Water Elevation (Meters)	133.91	102.74	364.36
Tail Water Elevation (Meters)	104.68	74	271
Gross Operating Head (Meters)	29.23	28.74	93.36
Av. Turbine Discharge (M3/S)	663	1260	377
Average Spillage (M3/S)	0	0	0
Average Total Station Disc -harge (M3/S)	663	1260	377
Computed Inflow (M3/S)	1068	1191	481
Storage Differential	405	-69	104
Maximum Level for Spillage Commencement	141.73	103.3	359
Minimum Level below which No Generation	137	99	355

3 METHODOLOGY

The process of calculating losses within the transmission and generation subsystems of the network involved the following steps.

3.1 Loss in the Transmission Subsystem

The transmission subsystem losses were initially determined using the power flow and loss approach before applying Kroon's loss formula. The following steps were undertaken to compute power loss in the transmission subsystem: Gathering relevant network data, including the Single Line Diagram (SLD) to determine line lengths, followed by the calculation of resistance per unit length. Computing losses based on power flow analysis. Determining the elements of the loss coefficients. Calculating transmission loss using Kroon's loss formula.

3.2 Calculation of B-Coefficients

The current distribution factor and power factor, which are essential variables for determining loss coefficients, are calculated first. The computation process is as follows: Peak load demand (i_{k1}, i_{k2}, i_{k3}… i_{k8}) on each element (generator bus) obtained from the system operator are; 500, 360A, 0, 0, 529A, 42.9A, 21A and 410A [14] respectively. Therefore, I_L = 1862.9A. Hence, the distribution factors d_{k1}, d_{k2}, d_{k3}… d_{k8} are given as:

$$d_{kn} = \frac{I_{kn}}{I_t} \tag{5}$$

Therefore d_{k1}, d_{k2}, d_{k3}, d_{k4}, d_{k5}, d_{k6} and d_{k7} are abstain as 0.27A, 0.19A, 0, 0, 0.28A, 0.02A and 0.01A respectively. Phase angles $\emptyset_1, \emptyset_2, \emptyset_3, \dots, \emptyset_8$ are obtained as follows:

$$COS\emptyset = \frac{P}{VI} \tag{6}$$

Where P = real power from generator bus, V = Voltage from generator bus. I = Current from generator bus.

3.3 Calculation of Elements of Loss Coefficient Matrices

The loss coefficient matrix (B) is symmetrical. The diagonal and off-diagonal elements of the matrix are determined as follows [15]. Off-diagonal elements:

$$B_{mn} = \frac{\cos(\delta_m - \delta_n) \sum d_{km} d_{kn} R_k}{|V_m||V_n| \cos\theta_m \cos\theta_n} \tag{7}$$

Diagonal elements:

$$B_{mm} = \frac{1}{|V_m|^2} * \frac{1}{(\cos\theta_1)} \sum d_{km}^2 R_k \tag{8}$$

Where R_k = resistance of the network element, δ_n = voltage angle, d_k = distribution factor, $Cos\theta$= generator bus power factor, $|V_m|$ = Voltage magnitudes which are obtained from power flow. Calculation of B_{io} and B_{oo}. The linear factor, B_o is given as [16].

$$B_o = \sum_{i=1}^{n} B_{oi} P_{gi} \tag{9}$$

The constant factor, B_{oo} is given as

$$\text{Boo} = \sum_{i=1}^{N} P_{\text{di}} \text{B}_{\text{ij}} \text{P}_{\text{dj}} \tag{10}$$

Calculation of loss using George‟s formula. P_{gi} = [5.85 4.5 3.12 0.65 0.00 4.24 2.9 4.5]. $P_{gj} = P_{gi}'$.

$$\text{PLGeorge's} = \text{Pgi x Bij x Pgi'} \tag{11}$$

Therefore, the real power loss calculated using George‟s formula is equal to 5.7175 per unit.

3.4 Calculation of Transmission Loss Using Kron's Formula

The real power loss (PL) is determined using Kron's Loss Formula and is calculated as follows:

$$\text{PLKron's} = \text{PG} + \text{BO} + \text{BOO} \tag{12}$$

Where P_G = Real power loss using George's loss formula, B_o = Linear coefficient factor, B_{oo} = Constant factor. When multiplied by the base value, the power loss is obtained as $P_{Kron's\ Loss}$ = 542.37 MW.

3.5 Loss in the Generation Subsystem

In the generation system, **losses** are determined by calculating the difference between the energy content of the fuel input and the power output from the generator. In practical applications, utility operators monitor and update four key characteristic curves**:** Fuel Input-Power Output Curve **–** Represents the relationship between fuel input (expressed in Btu/h **or** Kcal/h) and power output (in MW**).** Heat-Rate Curve **–** Shows the ratio of fuel input to the corresponding power output, plotted against power output. Incremental Heat Rate Characteristic **–** A plot of dF/dP (change in fuel input per unit change in power output) against power output. Cost Curve **–** Derived by converting the coordinates of the input-output curve from Btu/h to $/h [17]**.** Most utility operators represent the cost curve using either a quadratic or cubic polynomial of the power output, known as the cost function**.** The quadratic polynomial is more commonly used [14, 9]**,** and it is mathematically defined as:

$$C_f(P) = aP^2 + \beta P + \gamma \quad \$/hr \tag{13}$$

Where C_F (P) is the cost function, P is the power output, α, β and **ϒ** are called cost coefficients. The cost of electrical energy production is made up of the Operations and Maintenance costs and the fixed costs which include facility construction, salaries, taxes and insurance. The fixed costs are independent of the generator's MW output. For the quadratic cost model of equation (9), therefore, the „**ϒ**‟ coefficient which is fuel costs independent represents the fixed cost and the „α‟ and „β‟ coefficients which are fuel cost dependent are the operating costs [18]. Fuel costs dominate the operating costs necessary to produce electrical energy from the plant so that the fuel costs (F_C) can be taken to be;

$$F_C(P) = aP_g^2 + bP_g \quad \$/hr \tag{14}$$

If the average price of fuel (natural gas) is, F_P = X **$** per million mm BTU and the conversion rate is;

$$1Btu/h = \ RWatts \tag{15}$$

Then the input power to a plant is**,**

$$P_{in} = \frac{F_c(P)}{X}\ R\ Watts \tag{16}$$

The power loss in a power plant is;

$$P_{Loss} = P_{in} - P_{out} \tag{17}$$

3.6 Loss in Hydro Plants

Before initiating a hydropower generation project, it is crucial to conduct a site survey to assess the available hydro power. In an ideal scenario without losses, all available hydro power would be fully converted into electrical energy. The amount of power that can be generated depends on two key factors: Flow – The volume of water that can be captured and directed to rotate the turbine generator. Head – The vertical distance the water falls before reaching the generator. The greater the flow (amount of water available) and the head (height of the fall), the more energy can be converted into electricity. The available energy for conversion is the potential energy stored in the volume of water held at a certain height. The potential energy per unit volume is given by:

$$\text{Potential Energy} = \rho gh \tag{18}$$

Where ρ = Density of water (10^3 Kg/m^3), g = Acceleration due to gravity, h = Height (head) of the water, P is the power available from a dam reservoir which is the power input to the plant [17] is given by:

$$P = \rho ghQ \tag{19}$$

Where Q is the water flow rate (volume of water flowing per second in m^3/second). The loss in hydro-plant is the difference between the available power from the dam reservoir and the power output from the plant.

3.7 Loss in the power system

Technical loss in the NNEPS is the sum of the loss in transmission network and generation subsystem.

4 RESULTS AND DISCUSSION

4.1 Line flow and line losses

The computed line flow and line losses are shown in Table 3.

Table 3. Line Flow and Losses

Line		Power at Bus and Line Flow		Line Loss	
From	To	P	Q	P	Q
1		5.850	-127.692		
	2	-3.650	121.542	2.200	-6.150
	19	2.200	-6.151	0.000	-7.801
2		4.500	0.000		
	1	-20.155	121.506	1.214	-0.036
	3	-2.446	-58.352	0.394	-0.479
	15	1.930	-4.365	0.000	-5.815
	16	25.171	-58.788	0.560	-2.835
	25	-6.026	13.090	0.132	-4.656
3		3.120	0.000		
	2	2.840	57.873	0.388	-0.479
	4	0.528	-67..574	0.335	-1.590
	15	1.556	7.221	0.007	-6.325
	16	-1.230	-0.092	0.045	-46.985
4		0.650	0.000		
	3	0.060	69.164	0.133	-1.590
	5	0.000	-10.075	0.000	-10.075
	7	2.900	0.000	0.004	-9.461
	9	-7.130	-17.992	0.006	-8.819
5		-6.210	0.000		
	4	0.000	-10.090	0.000	-10.090
7		2.900	0.000		
	4	2.900	0.000	0.004	-9.461
	8	2.900	0.000	0.004	-9.174
8		4.500	0.000		
	7	10.711	-28.661	0.024	-9.534
9		-1.781	-1.103		
	4	6.669	13.985	-0.007	3.254
	10	1.660	-1.555	0.000	-3.105
10		−1.660	-1.550		
	9	-1.660	1.553	0.000	3.101
	11	−1.661	−0.098	0.001	−3.260
	12	1.286	−3.162	0.001	−3.460
11		-5.100	-0.083		
	10	5.099	0.101	0.000	-4.881
12		−2.040	-1.480		
	10	-1.280	3.161	-0.001	-6.541
	13	2.005	14.021	0.001	6.254
13		-2.130	-0.439		

	12	2.015	-13.088	0.132	-5.589
14		-1.930	0.000		
	27	-1.930	1.930	0.001	-58.23
15		-3.690	-0.079		
	2	-25.010	80.850	0.276	-5.252
	3	-1.550	6.321	-0.006	4.567
16		-1.230	-0.360		
	2	-25.072	58.760	-0.560	-2.835
	3	-1.231	0.092	-0.046	-3.651
	17	1.275	−46.893	0.045	−46.985
	18	3.110	−3.165	0.000	−3.263
	20	7.054	−3.328	0.003	−0.440
	26	-5.668	2.447	0.021	31.257
17		-3.110	3.112		
	16	-1.270	46.893	-0.045	46.900
18		−2.200	−1.600		
	16	-3.100	3.164	0.000	7.082
	24	-2.200	1.600	0.001	-7.801
19		-3.580	-0.450		
	1	-2.200	6.151	0.000	7.800
	25	-0.124	0.001	0.013	-2.546
20		-1.250	-0.630		
	16	-7.050	3.328	-0.003	3.338
	21	-2.220	0.933	0.001	-2.100
	22	1.820	-0.933	0.000	-0.933
21		-0.400	0.000		
	20	2.221	-9.330	-0.000	-4.265
22		-1.820	0.000		
	20	-1.832	1.004	0.000	-1.900
	23	6.793	-23.118	0.211	-4.560
23		-2.760	0.000		
	22	-6.780	23.118	0.210	4.561
24		-0.224	0.000		
	18	2.200	1.600	0.000	7.801
25		0.123	-0.001		
	2	6.025	13.090	-0.132	-4.656
	19	-5.264	2.568	-0.000	-2.223
26		-1.228	-0.360		
	16	5.600	2.447	-0.022	-33.257
27		-1.930	1.931		
	14	1.932	1.931	0.000	58.23
	Total			5.495	-121.535

4.2 Loss coefficient matrix

The computed loss coefficient matrix is shown on Table 4.

Table 4. Loss Coefficient Matrix

0.0305	0.0214	0.0000	0.0000	0.0285	0.020	0.0010	0.0219
0.0214	0.0151	0.0000	0.0000	0.0200	0.0014	0.0007	0.0154
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0285	0.0200	0.0000	0.0000	0.0266	0.0045	0.0094	0.0205
0.0200	0.0014	0.0000	0.0000	0.0045	0.0001	0.0000	0.0007
0.0010	0.0007	0.0000	0.0000	0.0094	0.0000	0.0000	0.0007
0.0219	0.0154	0.0000	0.0000	0.2050	0.0007	0.0007	0.0158

4.3 Transmission Loss Using Kroon's Formula

The transmission loss in the network for the period under review [19], calculated using Kron's loss formula, was determined to be 5.4237 per unit, equivalent to 542.37MW.

4.4 Power Input to Thermal Plants

The calculated power input for each thermal plant is presented in Table 5.

Table 5. Power Input and Loss for Thermal Plants

S/N	Power Station	Tur-bine Type	Installed Capaci-ty (MW)	Power Generated P_g (MW)	Power Sent Out P_{out} (MW)	Input Fuel Cost F_c-αPg^2 ($/h)	Input power - 0.293 (MW)	Power loss (MW)
1	Egbin ST2-5	Gas Fired Steam	1320	288.71	280.18	6,366.06	630.15	349.97
2	Sapele (Steam)	Gas Fired Steam	1020	35.08	33.42	435.01	43.06	9.64
3	Delta (Ughelli) Gas	Simple Cycle Gas	972	440.85	431.57	230,516.05	22,817.98	22,386.41
4	Afam IV-V	Open Cycle Gas	977	0.00	0.00	0	0	0
5	Okpai Gas/Steam NIPP	Combined Cycle Gas	480	277.25	270.63	-	-	-
	Total							22,746.02

4.5 Power loss from hydro plant

The computed power loss from each hydro plant is shown in Table 6.

Table 6. Power Input and Loss from Hydro Plants

S/No	Power Station	Type	Installed Capacity (MW)	Head (m)	Discharge (m^3/s)	Input power (MW)	Output power (P_{out}) (MW)	Power loss (MW)
1	Kainji Hydro	Hydro	760	133.91	663	871.0	184.91	686.0
2	Jebba Hydro	Hydro	576.8	102.74	1260	1269.9	326.99	942.9
3	Shiroro Hydro	Hydro	600	364.36	377	1347.5	310.81	1036.7
		Total						2,665.7

4.6 Loss in the Nigerian National Electric Power System

The total loss in the generation and 330kV transmission subsystems of the Nigerian National Electric Power System is calculated as follows:

542.37MW + 22,746.02MW + 2,665.7MW = 25,953.99MW.

4.7 Discussion

The findings of this study reveal a considerably higher level of technical loss in the Nigerian power system compared to previous studies. Using Kron's loss formula, this study calculated the transmission loss at approximately 542.37 MW, which is significantly greater than earlier reports, which typically estimated transmission losses at around 100 MW [20]. Additionally, while previous research found technical losses in the transmission network to be approximately 1,207.25 MW, this study identifies a net technical loss of 25,953.99 MW for the entire Nigerian power system, including both generation and transmission losses. This substantial discrepancy underscores the severity of technical inefficiencies currently plaguing the Nigerian National Electric Power System (NNEPS). In terms of generation losses, earlier works highlighted a relatively small proportion of inefficiencies in generation plants, with some sources indicating low efficiency levels in thermal and hydroelectric plants. However, this study reveals more concerning inefficiencies, particularly in the thermal and gas plants. Only the Sapele Thermal Station achieved a relatively high efficiency of 81%, while the largest plant, Egbin ST2-5, operated at only 46% efficiency. Furthermore, the gas plants were found to be largely inactive or inefficient during critical periods, contributing to a considerable total generation loss of 25,411.62 MW, which accounts for almost 70% of the total fuel/power input. These findings align with previous studies that identified suboptimal performance in Nigerian power plants but provide a more in-depth and quantifiable assessment of the extent of generation inefficiencies. The recommendations from this study, such as using B-loss coefficients to model transmission losses and emphasizing the structural improvements needed in the power system, also expand on earlier works. While prior studies recognized the need for an upgrade to the transmission infrastructure, this study specifically calls for the implementation of a ring or loop system to minimize transmission losses, a solution not thoroughly explored in previous literature.

5 CONCLUSIONS

The system is unable to generate power equivalent to its generation capacity or transmit power in line with its transmission capacity, primarily due to the limitations of its physical infrastructure. Understanding how much of the generated power can actually reach consumers is crucial, which makes knowledge of technical losses in the system essential. The main objectives of this study were to analyze the single-line diagram of the network and estimate its technical losses. Recognizing the significant losses in the network enables system engineers, planners, and operators to strategize for expansion and improvement. To estimate these losses, the loss coefficient approach was utilized. This method expresses transmission loss as a function of the total output of all generating plants. Unlike a fixed value, this coefficient varies with load conditions. The advantage of this approach over other methods used by previous researchers is its ability to calculate transmission losses at any given time, provided the generating plant outputs are known. The study confirms that technical losses are inherent in the Nigerian National Electrical Power System, as is the case for any power system, regardless of its size. Specifically, technical losses in the 330kV transmission network and generation system of the Nigerian power grid have been analyzed and identified.

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