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Hydro-Thermal Optimal Power Flow Analysis of the 34-Bus Nigerian power Network

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Abstract: *This work studies the hydro-thermal optimal power flow solution of the 34-bus Nigerian power network. The need for this work is as a result of the dispatch approach adopted by previous works on the network. In previous works, the outputs of the hydro plants are always being fixed, while the thermal plants are economically scheduled. An existing algorithm based on decomposition approach has been adopted for this work. The network consists of nine thermal and three hydro stations with fifty-five transmission lines. The results of the study have been able to show that, the total cost of generation from thermal stations is ₦117,327,475.70 while the water worth values of Shiroro, Jebba and Kainji generating stations are, respectively, 53,168.06₦/Mm^3, 18,687.71₦/Mm^3 and 17,821.69 ₦/Mm^3. It has also been established that, some buses experience voltage magnitude limit violation.*

Keyword: *Optimal power flow, Water worth, Hydro-thermal, Decomposition, Nigerian power network*

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I. INTRODUCTION

Electrical power can be produced from fossil fuel, water, sunlight, wind, chemical reactions, etc. Sources from fossil fuel, water and wind utilise method that convert mechanical energy from prime mover to electrical energy. The type of generating plants depends on the source of energy that drives the prime mover. For example, plants whose source of energy is heat from burning of fossil fuel or nuclear fission are referred to as thermal plants while those whose source of energy is water are referred to as hydroelectric plants [1].

Higher fraction of electrical power generation worldwide is by the hydroelectric and thermal plants while alternative sources of generating electrical power such as wind, solar, geothermal, etc. contribute less to the global energy supplies. Different sources of electrical energy generation are categorised under the conventional and the non-conventional sources. The conventional energy sources used by power plants include hydro energy and fossil fuel while the non-conventional energy sources include solar energy, wind energy, geothermal energy, etc. The power plants that use these sources are explained below.

Hydro plant involves the conversion of the energy of water into mechanical energy in a turbine. The mechanical energy in the turbine is further converted to electrical energy with the help of an electric generator. The energy of water utilised for hydro power generation may be kinetic or potential. The kinetic energy of water is its energy in motion and is a function of mass and velocity, while the potential energy is a function of the height of fall of water called the *head*. The potential of hydroelectric energy is available where there is water flow and head [2].

The main advantages of hydroelectric power generation are that the plant is highly reliable, the operation and maintenance costs of the plant are very low, the plant has quick starting ability and can be brought on load within few minutes to respond to rapidly changing loads without loss of efficiency. The major disadvantages of the hydro station are the high initial cost of construction, dependence on water availability which also depends on rainfall, distance to load centre which makes the station to require long transmission lines and the negative environmental impact it has on human and animals.

Thermal power plants are designed and constructed to convert energy from fuel (coal, oil, gas, orradiation) into electric energy. The actual conversion is accomplished by a turbine-driven generator [1].

Unlike the hydro plant, thermal plant has a high running and maintenance cost. It is not environment friendly since burning of fuel causes pollution and it is not quick starting. Nonetheless, its advantages are that; it can be situated close to load centres, it offers high reliability since the source (fuel) of energy is not seasonal and its construction time is lesser than that of the hydro plant. Other sources of energy are from solar, wind, geothermal and so on.

Power systems that utilize hydro and thermal plants are usually referred to as hydro-thermal power systems. The optimal dispatch of generation in this type of system is usually complex when compared to an all thermal plants system [3]. The hydro-thermal optimal dispatch is usually with or without the consideration of power flow.

The hydro-thermal optimal scheduling (HTOS).problem without the consideration of power flow equations has been solved in the past with various approaches. These approaches are either deterministic or heuristic [4]. Among the deterministic techniques are the base load procedure [5], variational calculus [6], coordination equation [7], dynamic programming [8, 9], Pontryagin maximum principle [10], peak shaving [7], Langrangian relaxation method [11, 12], Newton's method [3, 13], nonlinear optimization method [14] and mixed-integer programming methods [15]. The heuristic methods include the genetic algorithms [16], evaporation rate–based water cycle algorithm [17], particle swarm optimization [18], evolutionary programming [19], clonal selection algorithm [20] and so on.

The hydro-thermal optimal dispatch problem with the consideration of power flow is usually referred to as hydro-thermal optimal power flow (HTOPF).

The HTOPF problem had been solved in the past with the progressive optimality algorithm [21], Newton iteration method [3, 22], interior point method [23], linear and non-linear programming [24, 25] and a hybrid of genetic algorithm and Lambda iteration technique [26]. All the listed methods have presented their successes in their solution procedure.

In a recent work [27], a Newton-based decomposition approach to the (HTOPF) problem has been solved. The performance of the developed algorithm has been tested on standard test systems and the simulation results have shown the effectiveness of the algorithm. The performance of the algorithm is further tested in this study to solve the HTOPF problem of the Nigerian power network.

A survey of available past literature on Nigeria power system network has showed that various works have been carried out on the optimization of the Nigerian power network. In [28-30], optimization of Nigerian power network was carried out without the inclusion of any form of Flexible Alternating Current Transmission Systems (FACTS) devices. The works of [31, 32] performed the optimization of the network with the inclusion of some FACTS devices. In all the optimization works carried out so far, the outputs of the hydro plants are always being fixed, while the thermal plants are economically scheduled. Fixing the hydro plants power outputs in HTOPF solution procedure cannot give the needed optimal results. In contrary to previous studies, this work has solved the optimization problem of the network with the optimal scheduling of both thermal and hydro plants power outputs, while ensuring systems security. The algorithm developed by [27] has been used for this work.

II. HYDRO-THERMAL OPTIMAL POWER FLOW PROBLEM DEFINITION

The HTOPF problem can be formulated as follows [3, 22, 23];
Minimize

$$F = \sum_{t=1}^{T}\sum_{j=1}^{nt}(a_j + b_j P_{jt} + c_j P_{jt}^{\ 2}) \ (\text{₦}) \tag{1}$$

subject to these equality constraints;

(a) hourly power balance constraints

$$\left.\begin{aligned} P_{it} + P_{dit} - P_{git} = 0 \\ Q_{it} + Q_{dit} - Q_{git} = 0 \end{aligned}\right\rangle \quad t = 1,2,3,\ldots,T \tag{2}$$

(b) available water energy constraints

$$q_h - \sum_{t=1}^{T} \alpha_h + \beta_h P_{ht} + \gamma_h P_{ht}^2 = 0 \quad (\mathrm{m}^3) \quad h = 1,2,3,\ldots,nh \tag{3}$$

and inequality constraints

$$\left.\begin{aligned} P_{git}^{min} \le P_{git} \le P_{git}^{max} \\ Q_{git}^{min} \le Q_{git} \le Q_{git}^{max} \\ V_{it}^{min} \le V_{it} \le V_{it}^{max} \\ V_{kt}^{min} \le V_{kt} \le V_{kt}^{max} \end{aligned}\right\} \quad t = 1,2,3,\ldots,T \tag{4}$$

Superscript *max* and *min*, respectively, stand for the maximum and minimum limits on the variables.

where
F is the total cost of generation for the optimization period.
t is the discrete time interval in hour.
T is the optimization period under consideration.
ng is the total number of thermal generator.
a_j, b_j and c_j are the cost coefficients of thermal station j.
P_{jt} is the real power output of thermal generator j at time t hour in MW.
P_{it} and Q_{it} are, respectively, the active and the reactive power injection at bus i during time t. it's given in (5).

$$\left.\begin{aligned} P_{it} &= V_{it}\sum_{k=1}^{nb} V_{kt}\,Y_{ik}\cos(\delta_{kt}-\delta_{it}+\theta_{ik}) \\ Q_{it} &= -V_{it}\sum_{k=1}^{nb} V_{kt}\,Y_{ik}\sin(\delta_{kt}-\delta_{it}+\theta_{ik}) \end{aligned}\right\rangle \qquad (5)$$

V_{it} and V_{kt} are the voltage magnitudes at buses i and k during time t, respectively.
δ_{it} and δ_{kt} are the voltage phase angles at buses i and k during time t, respectively.
Y_{ik} and θ_{ik} are, respectively, the magnitude and angle of the admittance of the line connecting buses i and k together.
P_{dit} and Q_{dit} are the active and reactive power demands at bus i during time t, respectively.
P_{git} (MW) and Q_{git} (Mvar) are, respectively, the scheduled active and reactive power generations at bus i during time t (it can either be from the thermal station (i.e. P_{jt}) or hydro station (i.e. P_{ht})).
q_h is the pre-specified amount of water needed for generation at hydro station h during the optimization period.
α_h, β_h, and γ_h are the discharge coefficients of hydro station h.
P_{ht} is the real output power of the hydro station h at time t hour in MW.
nh is the total number of hydro stations.

III. DECOMPOSITION SOLUTION APPROACH TO HTOPF PROBLEM USING NEWTON'S APPROACH

In the work of [27], a Newton-based decomposition solution approach to the HTOPF problem was developed to solve the problem represented by Equations (1-4). In the work, the optimization period under consideration is divided into hourly time intervals. The optimization problem for each time interval is then solved using the Newton-Raphson based solution technique. After solving for all the time intervals, the results associated with each hydro plant are used to adjust the water worth value for each plant. This procedure is repeated until the available water is optimally utilized. A brief mathematical description of the technique is explained below.

The first approach to the development of the solution technique is by augmenting the power balance constraints of Equation (2) and the hourly discharge characteristics contained in Equation (3) with the hourly total cost of generation. The resulting hourly augmented Lagrangian function is given in Equation (6). The optimization intervals under consideration dictate the number of Langrangian functions to be minimized. For example, if twenty-four hour is to be considered, the solution procedure minimizes twenty-four Langrangian equations.

$$\begin{aligned} L_t(z,\lambda,\upsilon) &= \sum_{j=1}^{nt}(a_j + b_jP_{jt} + c_jP_{jt}^{\,2}) + \sum_{h=1}^{nh}\upsilon_h(\alpha_h+\beta_hP_{ht}+\gamma_hP_{ht}^2) + \\ &\quad \sum_{i=1}^{nb}\lambda_{pit}(P_{it}+P_{dit}-P_{git}) + \sum_{i=1}^{nb}\lambda_{qit}(Q_{it}+Q_{dit}-Q_{git}) \end{aligned} \qquad t=1,2,3,\ldots,T \qquad (6)$$

where

$$z=\{\delta_{it}\quad \delta_{kt}\quad V_{kt}\quad V_{it}\quad P_{git}\} \qquad (7)$$

$$\lambda=\{\lambda_{pit}\quad \lambda_{qit}\} \qquad (8)$$

$$\upsilon=\{\upsilon_h\} \qquad (9)$$

λ_{pit} is the Langrange multiplier relating to the active power balance equation at bus i during time interval t
λ_{qit} is the Langrange multiplier relating to the reactive power balance equation at bus i during time interval t
υ_h is the water worth or water conversion factor for an optimization period
The optimal solution to Equation (6) is achieved by meeting the Karush-Kuhn-Tucker (KKT) condition for optimality.
It is important to note the following;

(a) The second term of Equation (6) represents the discharge characteristics of the hydro plants.
(b) Equation (6) does not cater for the water energy constraint of Equation (3). This constraint is however considered after minimizing all the *T*-Lagrangian equations.
(c) The consideration of water availability constraint involves the evaluation of q_h and checking if Equation (3) is satisfied. If it is not satisfied, Equations (10) and (11) are used to update the water worth value. The updated water worth value is used for the next iteration to minimize Equation (6).
(d) This procedure continues until the water worth value tracks the available water.
The flow chat that summarizes the procedure is given in Figure 1.

$$\Delta\upsilon_h^{(m)} = -\frac{\Delta q_h^{(m)}}{\left(\frac{1}{2\gamma_h v_h^{3}}\sum_{i=1}^{T}\lambda_{pit}^{2}\right)^{(m)}} \tag{10}$$

where Δq_h is the deviation of the calculated total water discharge from the water availability q_h at iteration *m*. Therefore, at iteration *m + 1*, the water worth value is adjusted using Equation (11).

$$\upsilon_h^{(m+1)} = \upsilon_h^{(m)} + \Delta\upsilon_h^{(m)} \tag{11}$$

This procedure was implemented using MATLAB software. The software was used to solve various power systems' problem. This study has further used the software to analyse the HTOPF solution of the Nigerian power network.

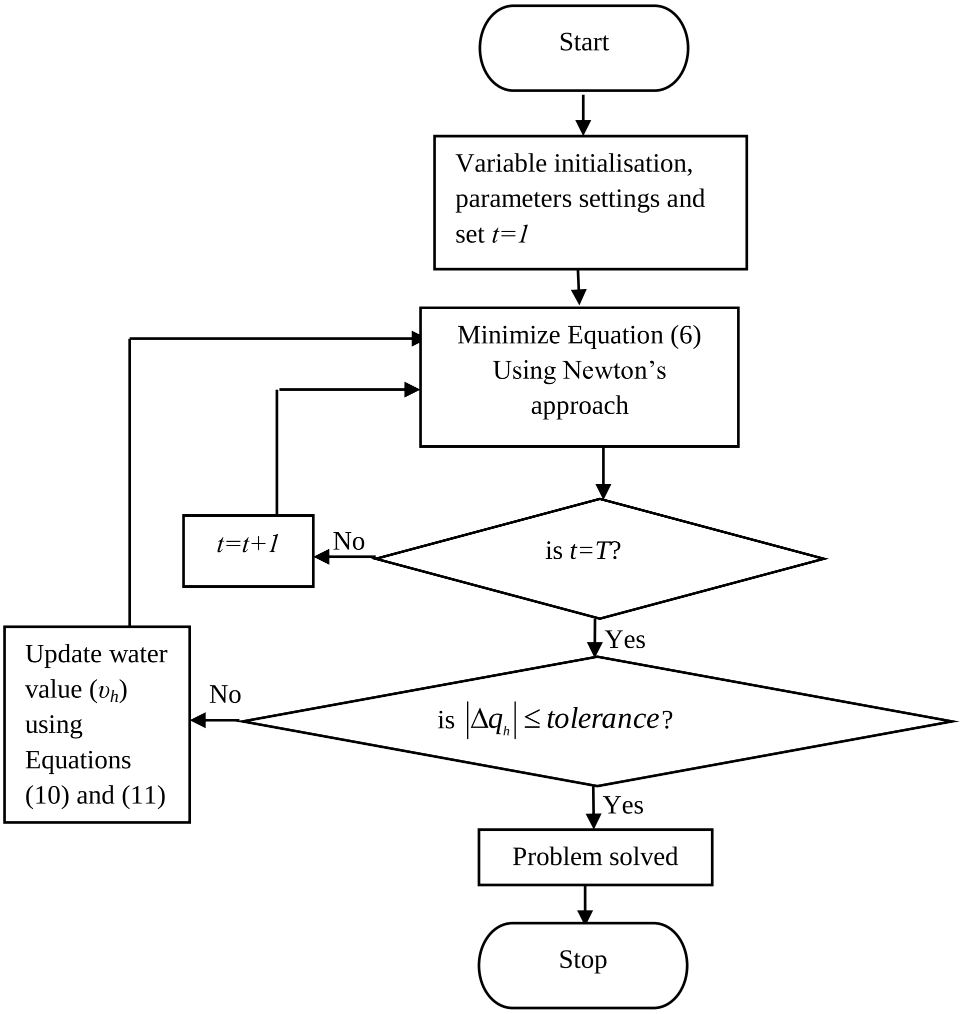

Fig. 1. Flow chart for the decomposition technique

IV. DESCRIPTION OF THE 34-BUS NIGERIAN POWER NETWORK

The 34-bus Nigerian power network has thirty-four nodes, fifty-five transmission lines, nine thermal plants and three hydro plants. The thermal plants are located at Egbin, Olorunsogo, Omotoso, Delta, Sapele, Geregu, Okpai, Afam and Asco. The hydro plants are located at Kainji, Shiroro and Jebba, the one line diagram of the system is shown in the appendix section. The data for the Nigerian network was sourced from [31, 32]. The quadratic cost functions for the Nigerian network thermal generating units have been developed as the best curve fits to their actual operating cost in a least square sense. The discharge characteristics for the Nigerian network hydro generating units have also been developed as the best curve fits to their actual operational discharge using least square curve fitting. The quadratic cost and discharge characteristics are, respectively, shown in Tables 1 and 2. Table 2 also shows the water availability (q_h) considered for this work. The minimum active power considered in this work is zero while the maximum is shown in Tables 1 and 2. It should be noted that the maximum real power considered is the available capacity of each plant. The load curve used for this work is shown in Figure 2.

Table 1: Quadratic Cost Coefficient for the 34-Bus Nigerian Network Thermal Generators

Bus No	Bus Name	a (₦/hr) × 10	b (₦/MWh) × 10	c (₦/MW^{2}h) × 10	P_{jt}^{max} (MW)
1	Egbin GS	22119.512	109.5322	0.054	1320
7	Olorunsogo GS	5357.134	54.08642	0.382625	835
9	Omotosho GS	254.6284	119.1767	0.912229	335
24	Delta GS	9056.426	53.77682	0.279867	900
26	Sapele GS	6797.576	49.10473	0.446701	870
29	Geregu GS	18046.11	34.82421	0.204649	414
30	Okpai GS	1007.952	180.3967	0.001471	480
33	Afam GS	12739.27	48.57949	0.253965	1001
34	Asco GS	1354.8845	166.3612	0.05556	201

Table 2: Discharge Coefficient for the 34-Bus Nigerian Network Hydro Generators

Bus No	Bus Name	γ (m^3/MW^{2}hr)	β (m^3/MWhr)	α (m^3/hr)	q_h (m^3)	P_{ht}^{max} (MW)
13	ShiroroGS	0.64818	3731.047	109294.7	29357217.36	600
14	JebbaGS	2.77213	9247.142	1045755	104766171.4	578.4
15	KainjiGS	13.09687	8920.093	125612.7	28244438.71	760

Fig. 2. Load Curve for the System

V. RESULTS AND DISCUSSION

5.1 Results for 34-bus Nigerian power network

The HTOPF solution of this network has been achieved in twenty-three iterations with an absolute maximum water mismatch of 4.47×10^{-07}. The total cost of generation from thermal stations is ₦117,327,475.70 while the water worth values of Shiroro, Jebba and Kainji generating stations are, respectively, 53,168.06₦/Mm^3,18,687.71₦/Mm^3 and 17,821.69 ₦/Mm^3. The total energy generation and transmission loss are, respectively, 84,593.6 MWH and 2,266.9 MWH. The graph that shows hourly demands and generation is shown in Figure 3. The differences between the hourly demand and generation amount to the transmission loss for every hour. This loss amounts to 2.68% of the total energy generation. Figure 4 shows the hourly percentage loss of the system. A close look at the figure shows that the shape is a mirror of Figure 2. The implication of this is that, the more the demand on the system, the lesser the percentage transmission loss. The active schedules of all the generators are displayed in Figure 5. The almost constant power outputs presented for Geregu, Okpai and Asco generating stations at some hours (in Figure 5) is as a result of the upper power limits of these stations. The maximum and minimum generation are, respectively, 4,616.2 MW (at hour 7) and 2,493.6MW (at hour 3). Figure 6 shows the hourly thermal, hydro and total generation. The contribution of the hydro station to the total generation is 19.97 % while the average hydro plant energy (AHPE) from Shiroro, Jebba and Kainji generating stations are, respectively, 228.34 MWH/Mm^3, 73.99 MWH/Mm^3 and 86.30 MWH/Mm^3. The values for the AHPE show that Shiroro generating station best maximises water when compared to other hydro plants. AHPE for hydro plant h has been calculated using Equation (12).

$$\text{AHPE}=\frac{\sum_{t=1}^{T}P_{ht}}{q_h} \qquad (12)$$

A minimum voltage magnitude of 0.85 pu was consistently achieved at Kano. This is as a result of the length of the radial transmission line (230-km) which connects Kano to Kaduna and the high demands at Kano. Similarly, high voltage magnitude was also consistently recorded at Jos, Gombe, Damaturu and Yola. This is also as a result of the length of the radial transmission line connecting Kaduna to Jos to Gombe to (Damaturu and Yola) which adds up to 642-km to Damaturu and 679-km to Yola. Also, the loads at these buses are low with the lowest at Yola. High line capacitance led to a build-up of reactive power on the transmission-line and with the low load demands, there will be high voltage magnitude at these buses.

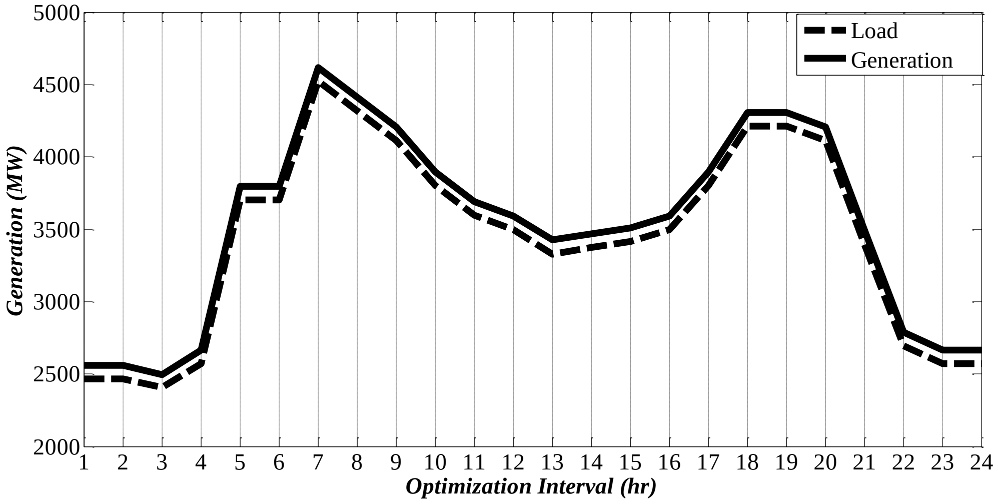

Fig. 3. Hourly Demand and Generation

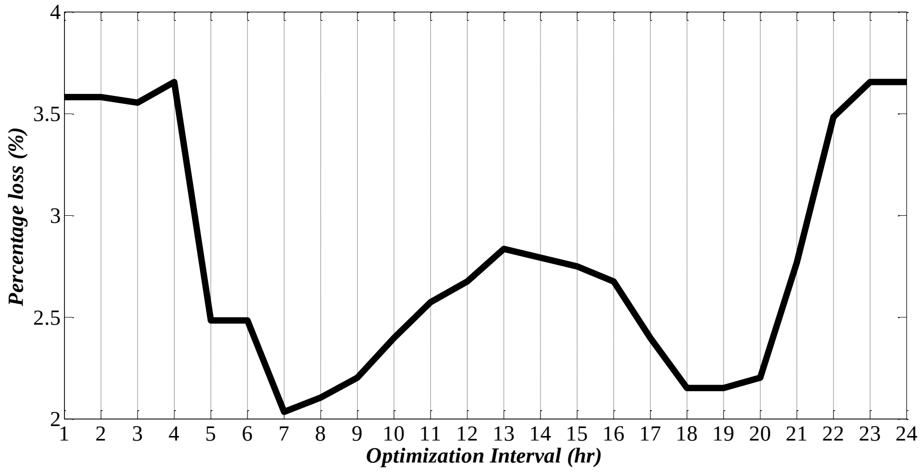

Fig. 4. Hourly Percentage Loss

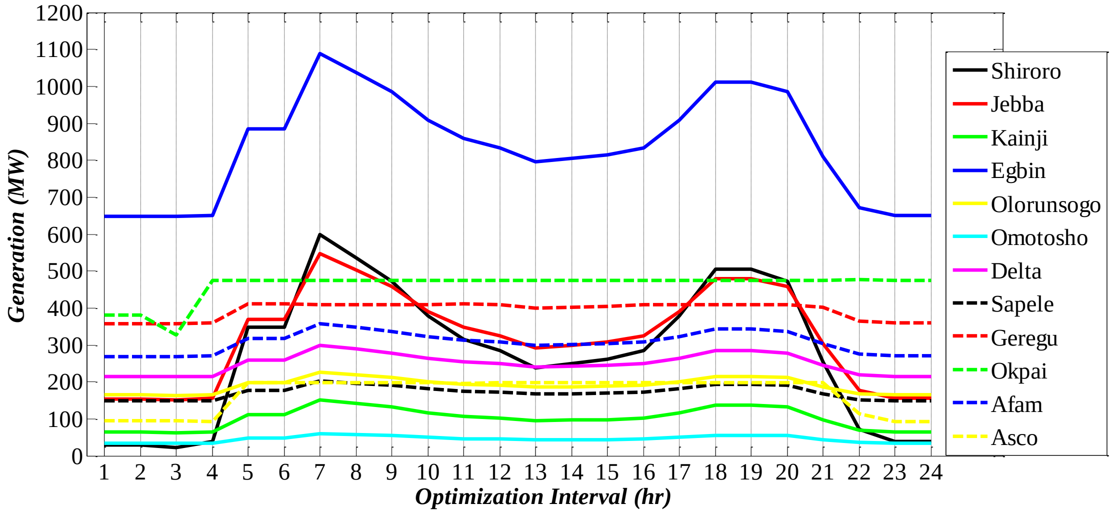

Fig. 5. Hourly Active Schedule of Generators

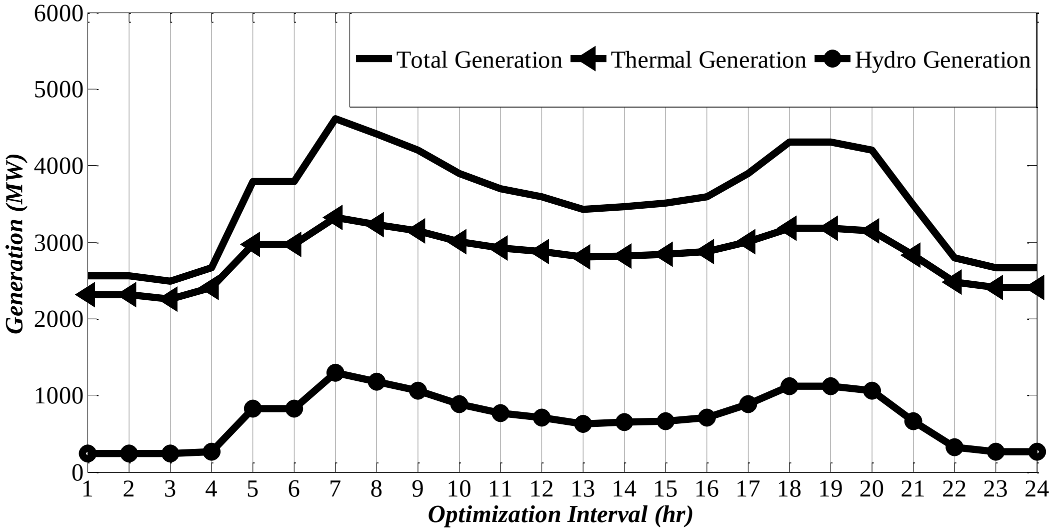

Fig. 6. Hourly Active Power Generation for the Hydro-Thermal System

VI. CONCLUSION

A decomposed Newton-based method of solving the HTOPF problem has been used to solve the Nigerian 34-bus power network. Unlike other works on the system which fixed the power outputs from the hydro plants, while the power from the thermal plants are optimally scheduled, this work has successfully carry out an optimal power dispatch of both the thermal and hydro plants. From the results obtained, it has been shown that;

(a) Hydro plants contribute significantly to the total generation of the network.

(b) The system suffers from voltage magnitude limits (0.9-1.1pu) violations due to length of some transmission lines and magnitude of demand at the affected nodes.

(c) The more the demand, the lesser the percentage loss experienced in the system.

As part of further work, the HTOPF problem of the system should be carried out with the inclusion of some FACTS devices, such as the Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM). These two devices have the ability to flexibly control the voltage magnitude violations noticed in the system.

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APPENDIX

Find below the one-line diagram of the 34-bus Nigerian power network.

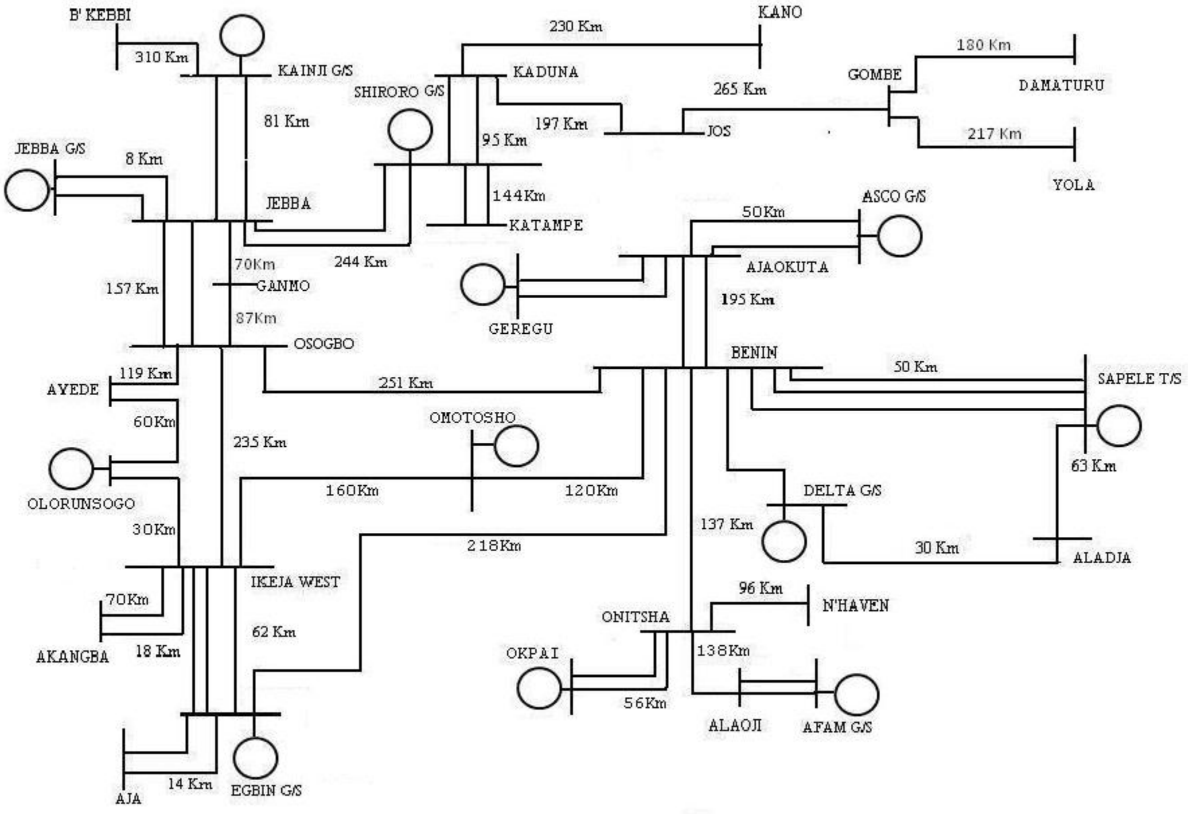

Fig. A.1. 34-Bus Nigerian Power Network

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