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Choosing the Power Injection Network Node based on Overall Minimum Losses: The Case of the 216-MW Kribi Natural Gas Power Plant in the Southern Interconnected Grid of Cameroon

By Tabe Moses, Tchuidjan Roger, Ngundam John & Manfouo Hervé
National Advanced School of Engineering - University of Yaounde I, India

Abstract- This paper proposes a method for the choice of the injection node of an incoming power plant into an existing grid. The southern interconnected grid (SIG) of Cameroon is used as an example to demonstrate the advantages of using the proposed methodology.

Given that the minimization of transmission losses constitutes a major cost-saving factor in electricity delivery, this work starts with the hypothesis that, if a power injection busbar is chosen within the existing grid such that the overall transmission losses are kept at a minimum, then it will be close to the load center, it will take care of the capability of the existing network to accommodate the new power injection, it will lead to increased reliability of power supply to several loads by providing for alternative supply routes, as well as result in a good voltage profile in the entire network. This paper therefore presents an approach for the determination of the power injection node of the lastly commissioned 216-MW Kribi natural gas thermal plant in Cameroon, based on the minimization of the overall network power losses.

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A Newton-Raphson load-flow solution with 34 busbars for the SIG of Cameroon is first developed in MATLAB, the overall network losses computed for successive injection into each of the existing network nodes, and the power injection busbar for the newly constructed 216-MW Kribi natural gas power plant determined based on the aforementioned criterium. It is observed that the injection node is close to the densely populated industrial city of Douala and the 384-MW reference hydropower plant of Songloulou can run with its full capacity. A comparison with the current interconnection busbar at Mangombe reveals that the cheaper hydro-generation of Songloulou must be reduced by about 76 MW to accommodate the more expensive incoming 216 MW from Kribi in the grid, and the overall network losses are increased by 73 MW. This explains why the Dibamba 84-MW thermal plant in proximity to the current injection node has been tripping off the network whenever Kribi gets connected with Songloulou running at its nominal output. Connecting at the node determined by this method thus makes additional 149 MW available for the consumer. Also, the injection mode determined with the new method is positioned in the SIG such that power supply to most of the loads is possible from two directions, thereby increasing supply reliability for such loads.

Keywords: power injection node, minimum network losses, newton-raphson, SIG, songloulou, kribi natural gas thermal plant, cameroon.

Author α σ ρ ω: Power Unit – Energetics and Automation Laboratory, National Advanced School of Engineering – University of Yaounde I – Cameroon. e-mail: tabemond@yahoo.com

I. Introduction

With the second highest hydroelectricity potential in Africa of over 50 GW for the already identified 110 potential sites, Cameroon promises to become a prime source of cheap renewable hydroelectricity both for her own economic growth and that of her northern neighbors like Nigeria, Chad, the Central African Republic (CAR), and even Niger. Power exchanges with southern neighbors like Congo, Gabon and Equatorial Guinea should also become necessary for improvement of reliability and sub-regional security. The development of new generation plants dictates a careful choice of the corresponding power injection busbar to ensure the most cost effective solution. The connection point of a new power plant into an existing grid has been given little scientific attention in the relevant literature, focus being given mainly to the determination whether the existing grid is capable of accommodating the new power injection, or what modifications would be required for that, and at what cost. With this approach, only a few busbars close to the targeted main load centre get considered for power injection. In Cameroon, the cost of the interconnection link and the proximity of the interconnection point to an existing supervisory control center have been advanced by the power utility corporation as additional reasons for the choice of a specific power injection node.

Recent problems in the Cameroonian grid with a total generation capacity of little over 1,000 MW and an 84-MW plant being tripped off upon connection of the new 216-MW Kribi plant have led the power unit research team of the National Advanced School of Engineering of the University of Yaounde I to carry out this study and provide more scientific insight into the phenomenon, as well as propose appropriate remedies.

Such proposals promise to be of particular interest in Cameroon whose political leadership aspires to bring the country to economic emergence by the year 2035 with an estimated electrical power consumption of about 6,000 MW [6] by then.

The methodology used consists of determining a load-flow solution for the entire SIG and then using the

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results to compute the overall transmission losses within the grid. This is first done without the incoming Kribi gas power plant. Kribi is then connected successively to all the busbars of the SIG, starting with the current situation of connection at Mangombe, and then comparing the overall losses for all the scenarios. The scenario with the least overall grid transmission losses is determined as the optimum node for the connection of the incoming power plant. For this purpose, a two-level program has been developed that uses the Newton-Raphson method first for the calculation of the load-flow and then a second level uses the load-flow results to compute the total transmission losses for the various injection nodes. The computation methods are presented below.

II. Application of the Newton-Raphson Method to Obtain the Load Flow Solution of the Southern Interconnected Grid of Cameroon [2,3, 5,9,10]

With the Newton-Raphson method the voltage magnitudes and angles at the various busbars are adjusted, causing variations in power until the residual deviation from the set values is reduced to zero. This method results from the development of the Taylor series for an equation f(x) = 0, when successive values are computed from an initial first order approximation as follows:

$$f(x) \approx f(x^k)+f'(x^k).(x^{k+1}-x^k) = 0 \tag{1}$$

Where $$f'(x) = \frac{\partial f}{\partial x} \tag{2}$$

$f'(x)$ is the Jacobian matrix of f(x). Starting with an initial value x^0, corrections Δx^k are obtained by solving the following system of linear equations:

$$-f'(x^k).\Delta x^k = f(x^k) \tag{3}$$

The new values x^{k+1} are obtained from the relation:

$$x^{k+1} = x^k + \Delta x^k \tag{4}$$

In the test grid, voltage magnitudes and angles have been adjusted based on the following two equations [9]:

$$\Delta P_i = P_i^{spe} - P_i^{cal} = V_i \sum_{j=1}^{n} V_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) \tag{5}$$

$$\Delta Q_i = Q_i^{spe} - Q_i^{cal} = V_i \sum_{j=1}^{n} V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) \tag{6}$$

With this notation, and dividing the Jacobian matrix into sub matrices, the load-flow problem becomes:

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix}^k = \begin{bmatrix}H & N\\ M & L\end{bmatrix}^k . \begin{bmatrix}\Delta V\\ \Delta\theta\end{bmatrix}^k \tag{7}$$

Dividing the variable ΔV by V delivers:

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix}^k = \begin{bmatrix}H & N\\ M & L\end{bmatrix}^k . \begin{bmatrix}\frac{\Delta V}{V}\\ \Delta\theta\end{bmatrix}^k \tag{8}$$

The system is thus described by the following matrix equation:

$$\begin{bmatrix}\theta\\ V\end{bmatrix}^k = \begin{bmatrix}\theta\\ V\end{bmatrix}^k + \begin{bmatrix}\Delta\theta\\ \Delta V\end{bmatrix}^k \tag{9}$$

Where: $$H_{ij} = \frac{dP_i}{d\theta_j}, M_{ij} = \frac{dQ_i}{d\theta_j}, \quad N_{ij} = \frac{dP_i}{dV_j}.V_j, L_{ij} = \frac{dQ_i}{d\theta_j}.V_j, \tag{10}$$

The Jacobian matrix contains the following elements [10]:

For i = j:

$$\begin{aligned} H_{ii} &= -Q_i - B_{ii}.V_i^2, \\ M_{ii} &= P_i - G_{ii}.V_i^2, \\ N_{ii} &= P_i - G_{ii}.V_i^2, \\ L_{ii} &= Q_i - B_{ii}.V_i^2 \end{aligned} \tag{11}$$

For i ≠ j

$$\begin{aligned} H_{ij} &= V_i.V_j(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}), \\ N_{ij} &= V_i.V_j(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}), \\ L_{ij} &= H_{ij}, \\ M_{ij} &= -N_{ij}, \end{aligned} \tag{12}$$

The values for active and reactive power at the busbars are obtained from the following relations:

$$P_i = \sum_{k=1}^{n} |V_i||V_k||Y_{ik}|\cos(\delta_k - \delta_i + \gamma_{ik}) \tag{13}$$

$$Q_i = -\sum_{k=1}^{n} |V_i||V_k||Y_{ik}|sin(\delta_k - \delta_i + \gamma_{ik}) \tag{14}$$

Each iteration $\left[\Delta\theta, \ \frac{\Delta V}{V}\right]$ is calculated by solving equation system (3). The process ends when $|\Delta P| \leq \varepsilon$ and $|\Delta Q| \leq \varepsilon$ (where ε is the specified tolerance, often in the order of 10^{-3}).

In this work the Newton-Raphson method has been applied with a MATLAB program to the SIG as depicted in the following flow chart:

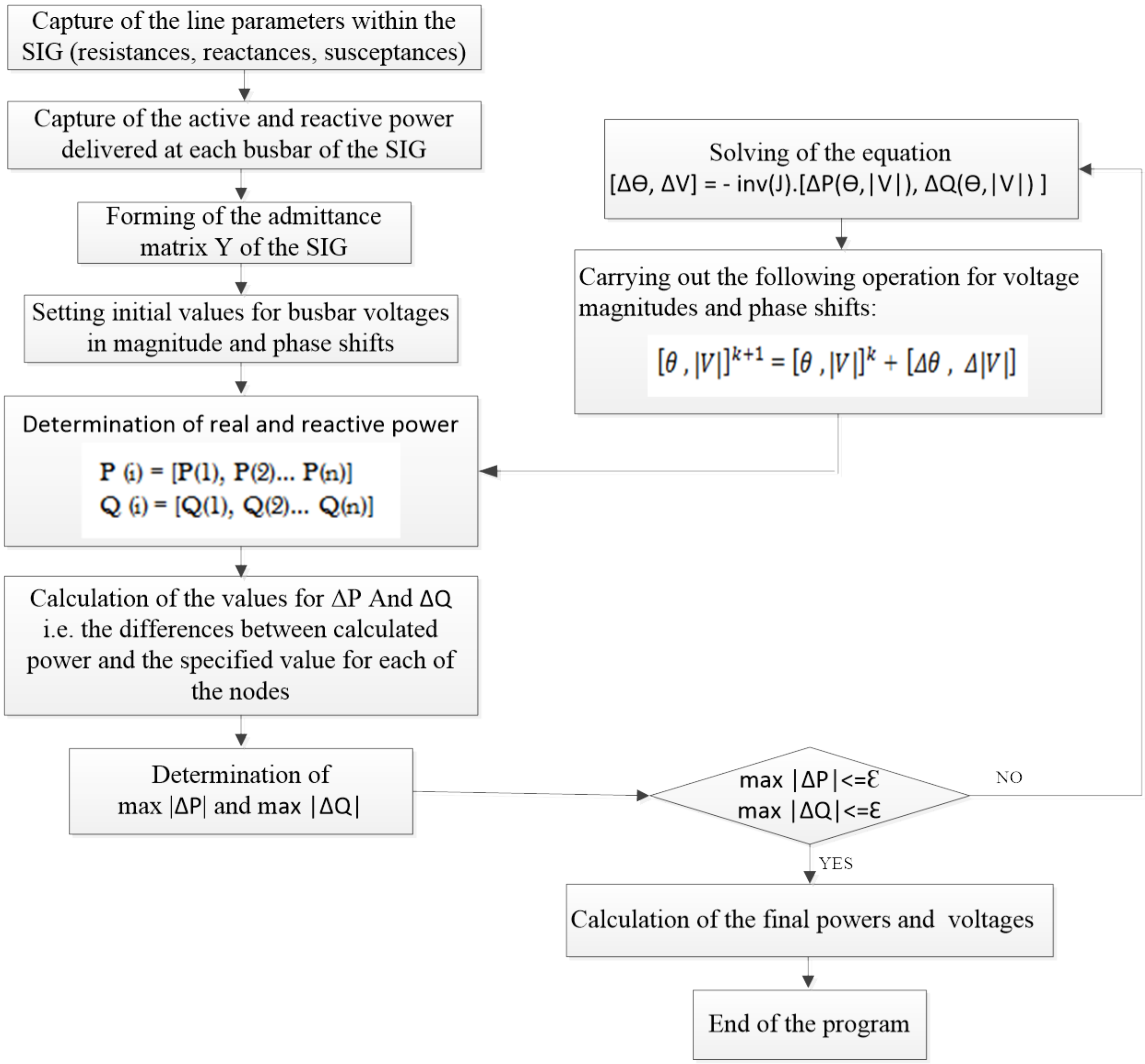

Figure 1 : Flow chart of the Newton-Raphson's method[8, 7]

III. Programming and Use of the Newly Developed Software

The developed software is used to compute the load-flow in the SIG. The level of exactitude of the results is verified using the IEEE 14-bus test network. The load-flow results are hence used to determine the overall transmission losses for that scenario. The software then connects the incoming 216-MW Kribi gas power plant successively to all the busbars of the network and determines the overall transmission losses for each scenario. By comparison of the transmission losses of the various scenarios, the optimum point of new power injection is determined as that for which the total transmission losses are least. In this part a presentation is made on how the software has been written in MATLAB version 7.8.0 and how it is used. The software comprises two menus, the first for load-flow and the second for the determination of transmission losses.

a) The menu for load-flow calculation

The software requires an input of all the electrical parameters of the grid under study, i.e. the SIG of Cameroon in this case. These parameters are:

- The total number of busbars;
- The total number of generation busbars (PV buses);
- The total number of load busbars (PQ buses);

- The complete electrical parameters of each busbar, viz:
  - For the slack bus: the voltage magnitude;
  - For generation busbars (PV buses): the generated and delivered active power, the generated and delivered reactive power and the voltage magnitude;
  - For load buses (PQ buses): the incoming and outgoing active power, the incoming and outgoing reactive power, and also the reactive power injected by shunt capacitors, where applicable;
- The interconnection lines in the grid with their electrical parameters (resistances, reactances, susceptances).

After processing the input data above, the software outputs the following results:

- The complete parameters of each of the busbars of the SIG, namely:
  - The active and reactive power injected at each busbar;
  - The voltage magnitude at each busbar;
  - The phase shifts of the various busbar voltages in degrees and radians;
  - The voltage phasor at each busbar;
  - The apparent power injected at each busbar.
- Using the determined complete parameters of all the busbars, the power-flow and transmission power losses are computed and displayed in absolute and relative values.

b) Determination of power-flow and transmission losses within the network [1, 8]

The π model of the transmission is chosen here for the analyses. Firstly, it is assumed that the power-flow is from node i to node j and the apparent power-flow is computed. The opposite direction is then assumed for the flow of power and again the corresponding value for the apparent power determined.

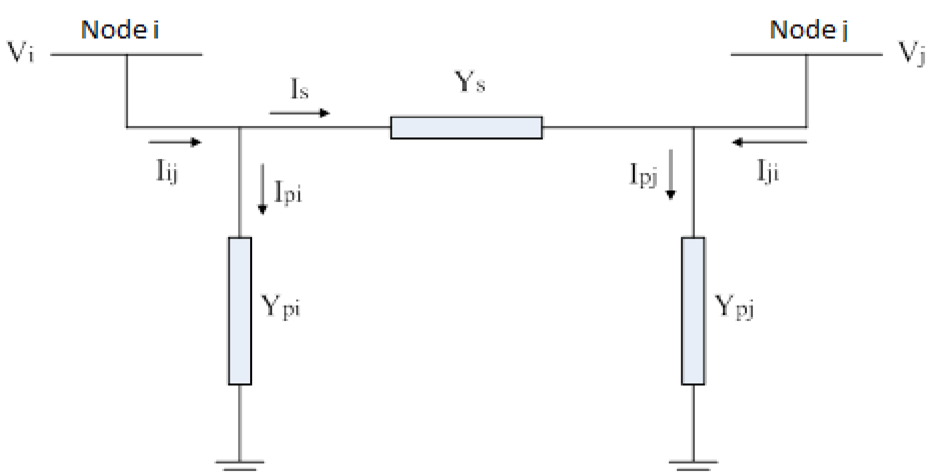

Figure 2 : π-Model of the transmission line [1]

Considering that the current I_{ij} is positive in the indicated direction, then:

$$I_{ij} = I_s + I_{pi} = Y_s(V_i - V_j) + Y_{pi} V_i \qquad (15)$$

Similarly, it can be written for the current I_{ji} in the direction shown:

$$I_{ij} = Y_s(V_j - V_i) + Y_{pj} V_j \qquad (16)$$

The complex power-flow S_{ij} and S_{ji} as viewed from the busbar i towards busbar j, and from busbar j towards busbar i, can be written:

$$S_{ij} = V_i I_{ij}^* \qquad (17)$$

$$S_{ji} = V_j I_{ji}^* \qquad (18)$$

The apparent power loss in this network branch (i.e. between nodes i and j) is therefore:

$$\Delta S_{ij} = S_{ij} + S_{ji} \qquad (19)$$

The overall losses within the network are hence obtained by summing up the losses in all the network branches.

The percentage loss is thereafter calculated using the relationship:

$$\Delta P_{\%} = \frac{\Delta P}{\sum P_{inj}} * 100\,\% \qquad (20)$$

$\Delta P_{\%}$: Relative percent active power lossin the network;

ΔP: Total percent active power loss in the network;

$\sum P_{inj}$: Sum total of active power injections into the network (i.e. differences between generated active power and consumed active power) at each generation busbar, including those of the slack bus.

c) Second Menu: Determination of the optimum interconnection point of an incoming power plant into an existing electricity grid

In this part the software needs:

- The complete parameters of the existing network before the connection of the new power plant as described in part 3-1;
- The parameters of the new plant to be connected, which are:
  - Its generated active power.
  - Its generated reactive power.
  - Its generated voltage.

The procedure used to determine the optimum point of power injection into the existing network by the new power plant is as follows:

i. The software connects the incoming power injection successively to each of the busbars of the existing network, with the exception of the slack bus. The slack bus at Songloulou remains the reference bus throughout the entire process. Noteworthy is however that:

✓ If the injection node is a PV bus, then it will remain a PV bus. The active and reactive powers generated by the new plant add to the values of the existing grid. The busbar voltage on the other hand remains same as before connection.

✓ If the busbar to which the incoming plant is connected is a PQ bus, it is automatically transformed into a PV bus. The generated powers (active and reactive) of the PV bus thus obtained are those of the incoming plant; the active and reactive powers consumed at the busbar remain the same as the values prior to the connection of the new plant. In this case the number of PV buses increases by one, and at the same time the number of PQ buses reduces by one.

ii. After the connection of the new plant to any busbar of the network, the software calculates the load-flow for the new network configuration using the same methodology as in part 3-1 above. It determines the power-flow and power losses in all network branches and uses that to compute the losses in all the network branches, as well as the percentage power losses. This software thus implements the same operations connecting (after having connected to the preceding busbar) this plant to another node, and as so on, until connection has been done to all the busbars of the network, except the slack bus.

iii. For every connection of the incoming plant to all the busbars of the network, and after performing the load-flow and transmission loss determination in each of the cases, the program stores the percentage losses.

iv. The node with the least value for the percentage loss is thus the optimum point for the power injection by the incoming power plant.

- After performing these operations, the results displayed by the program are as follows:
- A graph showing the percentage losses as a function of the various injection points. After determination of the various percentage losses following the connection of the incoming power plant onto all the busbars of the network, the program draws and displays the graph presenting these losses as a function of various injection nodes. This provides a visual guide permitting the user to judge and decide at a glance on the best power injection busbar.
- Also displayed are the overall losses after connecting the incoming plant to the busbar delivering minimum losses. This delivers an instant evaluation of the influence of connecting the new plant to that particular busbar.
- Power savings as a result of injection at the node delivering minimum overall network losses are also displayed. With a knowledge of the power losses before and after the injection at the busbar delivering minimum losses, the energy savings (these could theoretically be positive or negative!) due to the new choice of the injection nodeare made available.

IV. Application to the Southern Interconnected Grid (SIG) of Cameroon: The Case of the New 216-MW Kribi Gas Power Plant

The southern interconnected grid (SIG) of Cameroon consists of 34 busbars of which one (01) is the reference busbar, eleven (11) are generator busbars and twenty two (22) are load busbars. With two hydropower plants in Songloulou (384 MW) and Edea (264 MW), and three main thermal plants in Limbe (84 MW), Dibamba (86 MW) and the lastly commissioned 216-MW Kribi gas power plant, it produces and handles over 90% of the total consumption of electrical energy in Cameroon. There are also a few diesel driven plants that are used only for short peaking periods.

Without the new Kribi plant and the peaking thermal plants, the southern interconnected grid of Cameroon can be considered in a simplified manner from the SCADA substation of Mangombe as a radial network with two main axes supplying Yaounde and Mbalmayo on the one hand, and Nkongsamba, Bafoussam through to Bamenda on the other hand. This simplification is permissible since all the supplying plants, but for Limbe, are at a distance of less than 80 km (i.e. are linked with electrically short lines!) to Mangombe. The single-line diagram in that case would be as shown below:

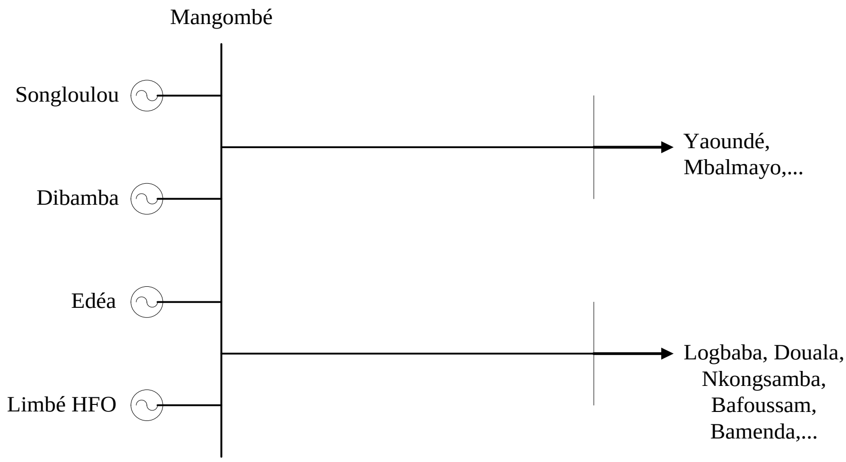

Figure 3 : Simplified one-line diagram of the RIS without the Kribi gas power plant

This diagram of Figure 3 shows the four main generating plants of the SIG connected to the SCADA substation of Mangombe, with two main emanating power corridors, one towards Mbammayo through Yaounde and the other towards Bamenda through Logbaba, Douala, Nkongsamba and Bafoussam. A simulation of this network with the newly developed software tool reveals that the overall losses are at the high level of almost 21% for active power and almost 36% for apparent power. This is far above the recommended highest value of 10% for active power [4], and leads not only to high operational costs but also to big voltage drops within the network.

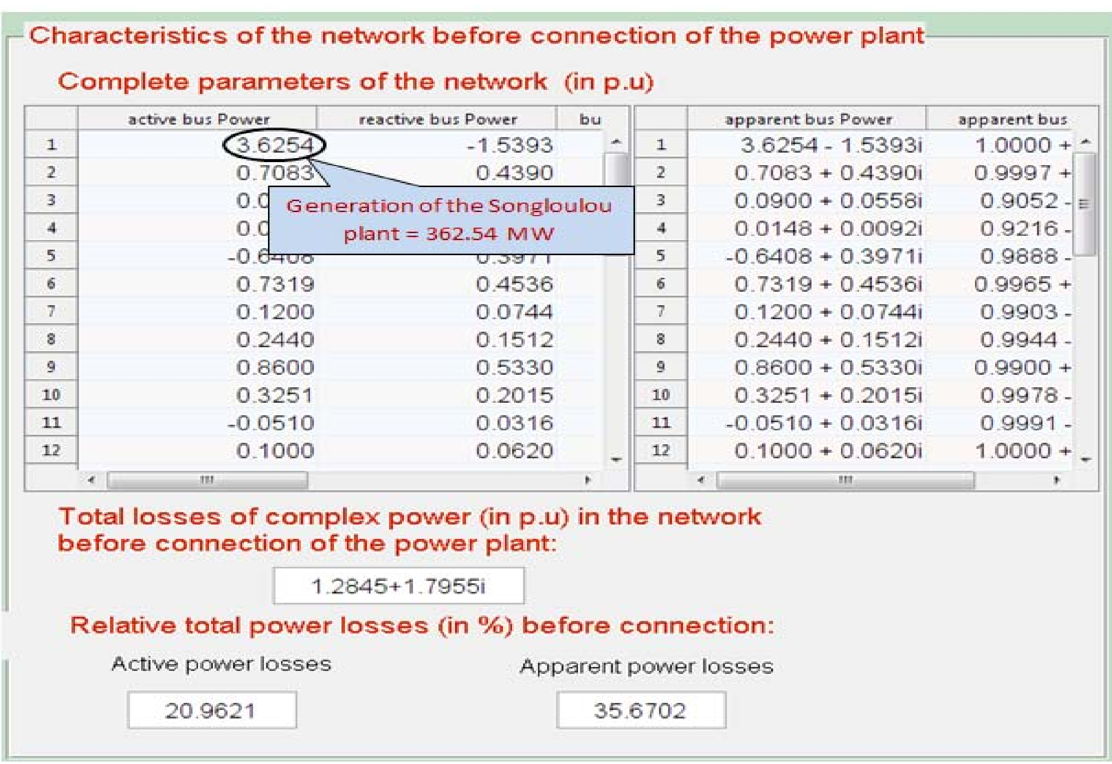

Figure 4 : Results of the simulation of the SIG without the 216-MW Kribi plant

Connecting the incoming Kribi gas power plant onto the Mangombe 225 kV busbar delivers the modified single-line diagram, still of a radial network, shown below:

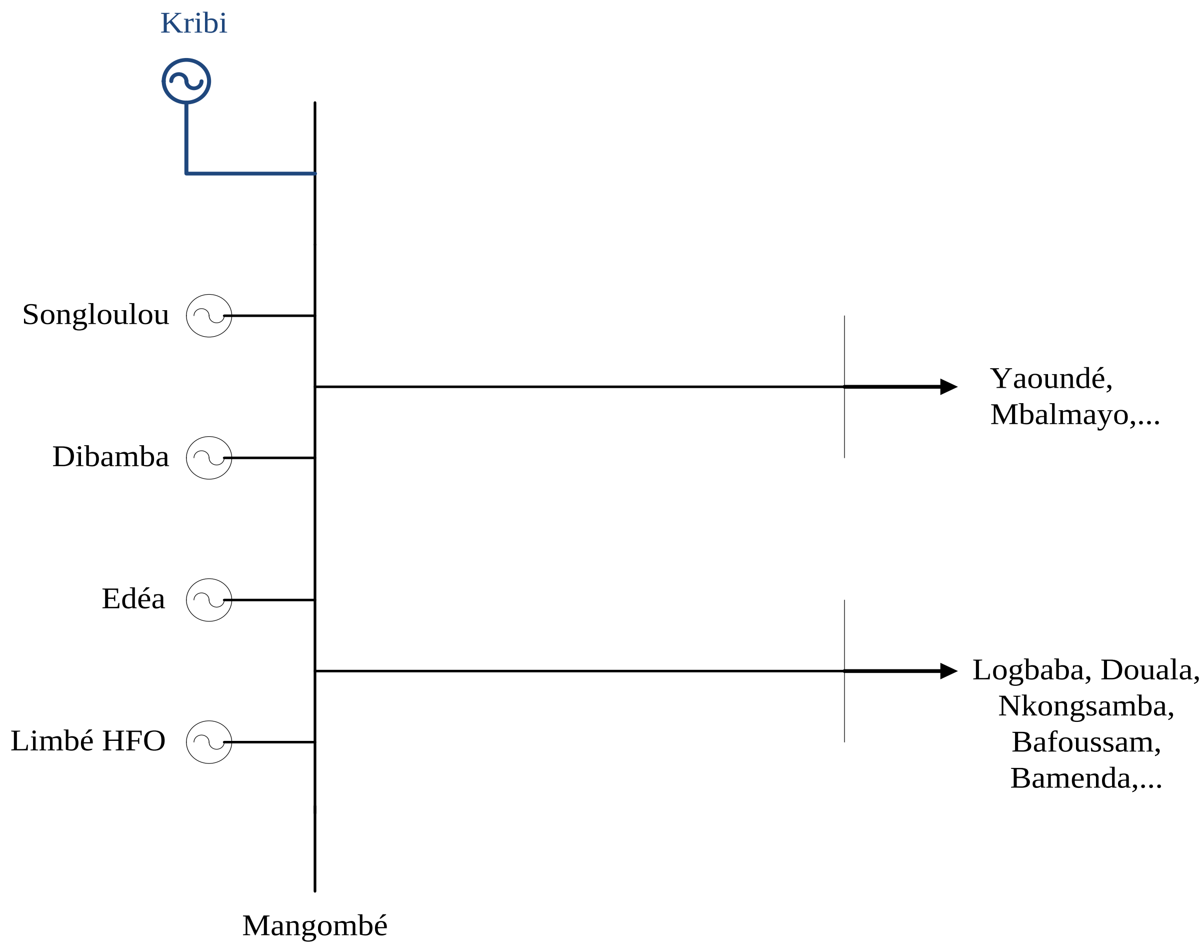

Figure 5 : Simplified one-line diagram of the SIG with Kribi connected to Mangombe

The simulation of this new grid configuration with the new software delivers higher losses than without Kribi connected. The relative active losses climb up from 21 % to 25 %, while the apparent losses move from 36 % to over 38 %.

Also noteworthy is that the generation of the biggest hydropower plant in the SIG, which is serving in the simulations as reference plant, is reduced by almost 91 MW automatically to keep the steady-state stability of the grid. From the point of view of exhausting the cheap hydropower generation for base-case load before turning over to the more expensive forms of electricity generation, this reduction is unacceptable in practice. It has been observed that the connection of Kribi to Mangombe provoked the disconnection of Dibamba, leading to modifications in the sensitivity of supervisory control and protection equipment by the utility company to accommodate the incoming plant. Even though this measure has made it possible to have Kribi running simultaneously with the other four plants, the new software reveals that the price to pay is increased transmission losses of almost 4 %, with a potentially weakened protection scheme.

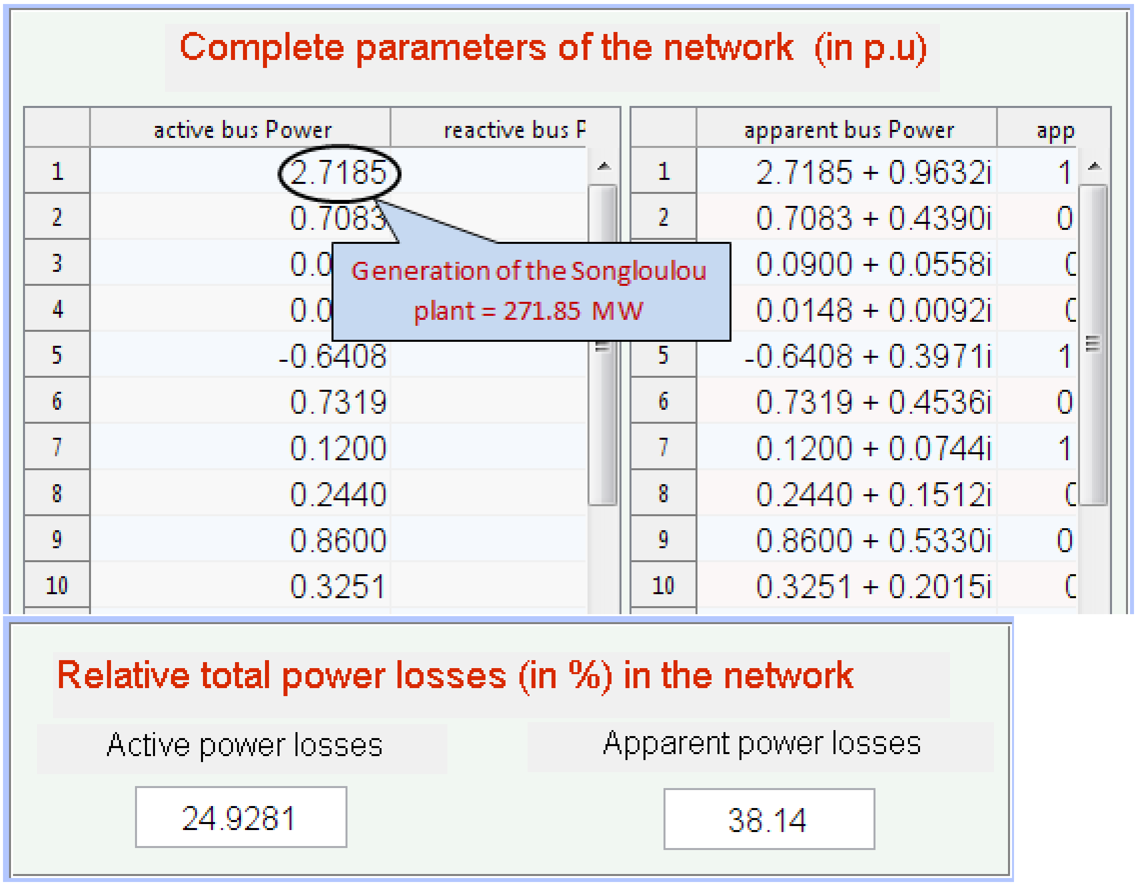

Figure 6 : Results of the simulation of the SIG after the connection of Kribi to Mangombé

Given the above results, the second menu of the new program is used to determine the injection node that produces the smallest overall losses in the SIG. For that purpose, Kribi is connected successively to all the busbars and the overall losses for each scenario computed. Figure 7 below shows a plot of the overall loss per site. Mangombe 225 kV is here site number 22 with a total relative loss of 24.93 %. Node 20 presents the least overall relative loss of 16.14 %. This node is Logbaba 225 KV. This site is thus determined by the new software as the optimum point for power injection of the new 216-MW Kribi gas power plant. The voltage profiles for connection to Mangombe and connection to Logbaba are presented in Table 1 below for purposes of comparison. Although the profiles are generally acceptable for most of the busbars in both cases, i.e. deviations of less than 5 %, the maximum deviation from the nominal value observed at busbar 33 is in the case of connection to Mangombe (-10.78 %) far higher than in the case of connection to Logbaba (-4.42 %). Logbaba therefore clearly offers a better voltage profile in the network.

Table 1 : Voltage profiles for Kribi connected to Mangombe and to Logbaba

Voltage profile for Kribi connected to Mangombe busbar				Voltage profile for Kribi connected to Logbaba busbar			
Node number	Voltage magnitude (in p.u)	Node number	Voltage magnitude (in p.u)	Node number	Voltage magnitude (in p.u)	Node number	Voltage magnitude (in p.u)
1	1	18	0.9947	1	1	18	0.9908
2	1	19	1.0099	2	1	19	0.9881
3	1	20	0.9893	3	1	20	1.0219
4	1	21	0.9909	4	1	21	0.9967
5	1	22	0.9852	5	1	22	1.0159
6	1	23	0.9870	6	1	23	1.0011
7	1	24	0.9767	7	1	24	1.0142

8	1	25	0.9968	8	1	25	0.9968
9	1	26	0.9034	9	1	26	0.9034
10	1	27	0.9640	10	1	27	0.9601
11	1	28	0.9603	11	1	28	0.9603
12	1	29	1.0001	12	1	29	1.0001
13	1	30	0.9981	13	1	30	0.9738
14	1.0396	31	0.9717	14	0.9996	31	0.9717
15	0.9880	32	0.9934	15	0.9947	32	0.9934
16	0.9980	33	0.8922	16	1.0099	33	0.9558
17	0.9929	34	1.0001	17	0.9887	34	0.9902

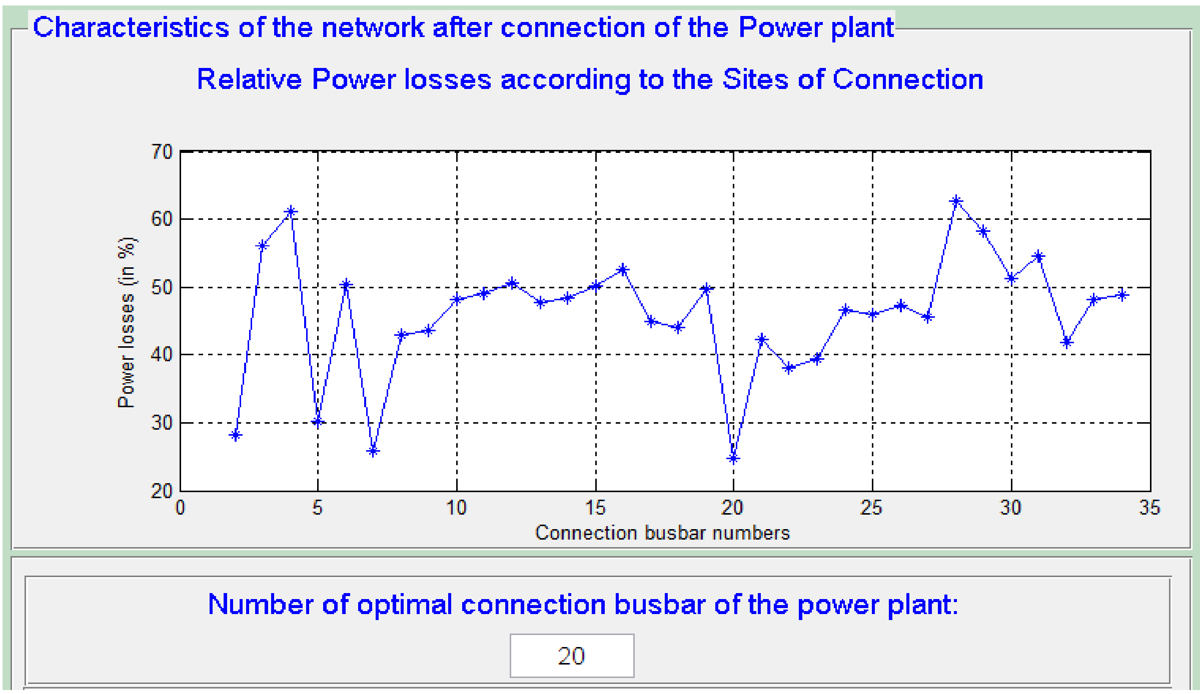

Figure 7 : Results obtained after successively connecting Kribi to all the busbars of the SIG

Below are the results obtained when Kribi is connected to the Logbaba 225 kV busbar:

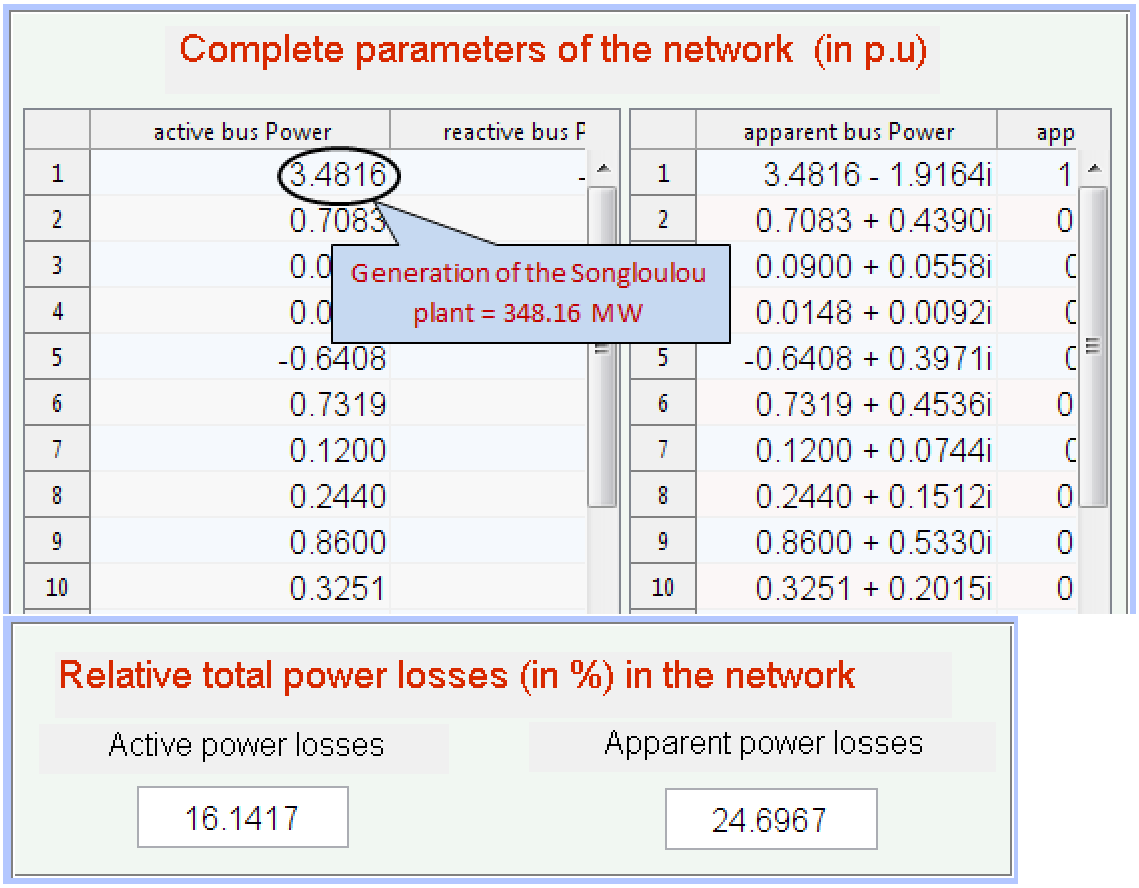

Figure 8 : Results of the simulation of the SIG after connection of Kribi to Logbaba

These results reveal that the cheaper generation of the reference Songloulou hydropower plant increases by 76.31 MW compared to the case when Kribi is connected to Mangombe. In addition, the total relative losses reduce by 8.78 %, corresponding to 72.82 MW. Therefore a total of 149.13 MW of power is made additionally available to the consumer simply by making the right choice of the power injection node with the proposed algorithm as done with the newly developed software, while gaining additionally in voltage profile and supply reliability.

Connecting Kribi to Logbaba modifies the simplified SIG to look thus:

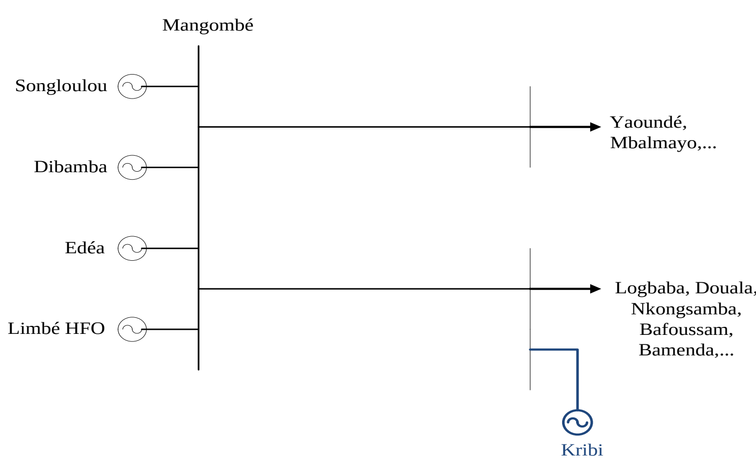

Figure 9 : Simplified one-line diagram of the SIG obtained by connecting Kribi to the Logbaba 225 kV busbar

It is evident that power supply now becomes possible from two directions creating the possibility not only to keep all the power plants running at nominal power, but also to increase the reliability of the power supply within the entire grid, while keeping the transmission losses at a minimum.

V. Conclusion

Points of injection of generated power into existing grids have been based on the power reception capability of the existing local network and the cost minimization of the interconnection link between the new power plant and the injection point close to the main load centre. Using the example of the most recent power plant commissioned in Cameroon, this paper establishes that when the minimization of the overall network losses is set as main criterion for the determination of the power injection node, a solution is obtained that not only takes care additionally of the power handling capability of the local network, but also delivers a good voltage profile while increasing supply reliability. For that purpose, a load-flow solution in MATLAB for the 34-busbar southern interconnected grid of Cameroon has been developed, tested and confirmed with results of the 14-bus IEEE test network. It is then used to determine the total transmission losses of the grid. The minimization of the overall grid transmission losses being a major cost saving factor in grid operation, this method will henceforth prove very useful in generation expansion projects.

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