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Incorporating Pumped Storage Power Plant in the Sri Lankan Electricity Sector

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Abstract: Sri Lanka is anticipated to experience a coal dominant electricity sector within this decade with the introduction of planned large scale coal power plants. Developing Pumped Storage Power Plant (PSPP) would be one of the most promising options to utilise the additional coal power and to effectively handle the peaking scenario. Comprehensive study on PSPP was carried out with the due considerations on the possible sites for the power plant, the electricity transmission aspects and the future load demand. As the first step, suitable site locations were selected for a new PSPP interconnection based on existing power plants such as Kotmale, Victoria, Polpitiya and Laxapana. The Sri Lankan transmission system was modelled using the Integrated Power System Analysis (IPSA) software package for two different load demand conditions in 2016. Then the technical feasibility was analysed in the modelled transmission network with the introduction of candidate PSPPs for different loading conditions. Each of the case in the study was established with the load flow, fault level study and transient analysis. Finally the optimum capacity for each power plant was estimated by comparing the voltage stability, overloading conditions and the overall transmission losses. This study anticipates assisting the policy makers and PSPP designers in selecting an optimal option to address the peaking scenario and the urgent electricity needs of Sri Lanka.

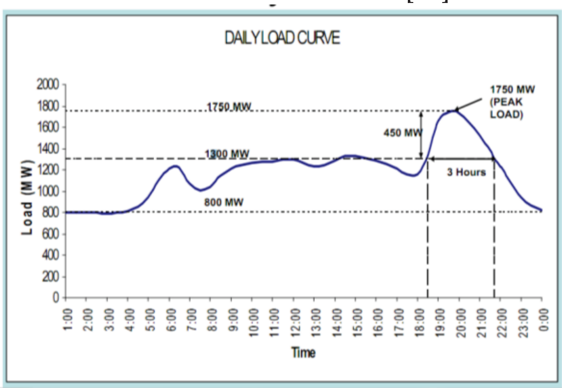
Keywords: Pumped Storage Power Plant (PSPP), interconnection, load demand

1. Introduction

A Pumped Storage Power Plant (PSPP) can primarily generate required electric power during the peak hours and can also absorb power from the supply grid during the off peak hours in order to pump water to the upper reservoir. It is widely acknowledged that Pumped Storage hydro can play an authentic and unique role in the modern power systems [1].

PSPP acts as an ideal fast response reserve assisting economic dispatch [2 - 4]. Since PSPP can store electric power, it improves the quality of the electricity supply and the reliability of the sector as a whole through the improved provisions for frequency control, reactive power supply and myriad others [5]. Owing to these advantages of PSPP it allows the power system to be developed with larger penetration of renewable energy sources in a flexible manner [6]. In a system inclusive of both thermal and non-thermal sources, PSPP acts as a steadfast intermediary in the overall system coordination [7].

Studies have indicated the potential for PSPP in Sri Lanka considering various aspects [8 - 10]. As in Figure 1, Sri Lanka witnesses a peak demand in electricity during 1800- 2100 hrs. It is estimated that 17% of the total energy is consumed during this time period. Owing to this peaking scenario, Sri Lanka needs to find a mechanism to serve the fluctuating demand. This paper suggests that PSPP could be one of the effective solutions when the daily load curve of Sri Lanka is not flattened [11].



Source: CEB

Figure 1 - Load Curve of Sri Lanka in 2007

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Since Noraicholai and Trincomalee coal power plants are planned to be fully connected to the grid within a decade, introduction of PSPP would increase the efficiency of these large scale coal power plants as well.

Furthermore, the maintenance costs of certain types of gas-fired power stations increase sharply burdening the national economy when they are forced to reduce load at night [12]. This is due to the fact that the thermal plants are much less able to respond to the sudden changes in electrical demand, potentially some are causing frequency and voltage instability. Pumped storage plants, like other hydroelectric plants, can respond to load changes within seconds.

It is possible to improve on this loading performance by operating the pumped storage units' spinning-in-air-either spin-pump or spin-generate. In these reserve modes, pumped storage units use less than 1 % of their rated power, but by opening water valves they can be changed to a pump or generate mode in approximately less than 10 seconds. Hence PSPP provides a technically viable prospect to the national electricity grid.

This paper presents the details of a feasibility study on PSPP considering the transmission aspects. Initially the whole transmission network of Sri Lanka in 2016 was modelled and the selected prospective PSPP was introduced into the system with a detailed analysis under selected options. Preliminary site selection study has also been presented for the prospective PSPP in accordance with the selected interconnections.

2. Methodology

A study was carried out to select the possible sites for the PSPP. Here contour maps and distance between the sites were considered. Entire existing electricity transmission system of Sri Lanka was developed up to the year 2016 using the Integrated Power System Analysis (IPSA) Software Package, with the predicted load demand and generation pattern [13 - 15]. The forecasted electricity supply demand was obtained from the long term transmission planning report considering the transmission line, transformer and auxiliary losses [14]. Both the night and day peak conditions were distinctively considered in developing the scenarios. Subsequently, the new candidate PSPP was introduced into the system. Analysis was carried out for selected interconnections of this new power plant to find the optimum capacity for each interconnection. The selected four interconnections for the new PSPP (Kotmale 220kV busbar, Victoria 220kV, Polpitiya 220kV and Laxapana 132kV) were used for further studies. Simplified illustration of the interconnection of PSPP to Kotmale 220kV bus bar in Case- 1 is given in Figure 2. The entire electricity network as in 2016 is in Annex-1.

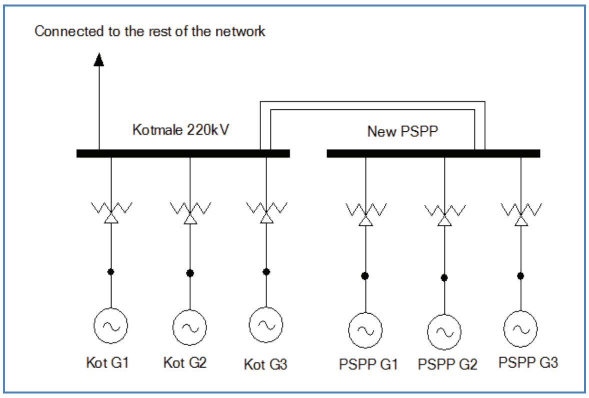


Figure 2- The interconnection of PSPP to Kotmale 220kV bus bar as in Case [Annex 1]

Load flow analysis under normal operating conditions, fault level study and transient analysis were carried out for each case with the selected optimum capacity of the power plant.

3. Site Selection Study

As mentioned in the long term generation planning report, expansion projects are under way in Kotmale (Capacity expansion), Laxapana (additional 72.5MW), Polpitiya (additional 23.2MW), Samanalawewa (2x60 MW generator units) and Victoria (additional 2x70MW) [14]. These five power plants are currently used for peaking purposes.

The site selection study was done based on location of resources and this resulted four possible sites to study a PSPP in Sri Lanka. The first option is introducing a new lower reservoir in Polpitiya and adding three new generating units along with the Polpitiya Power Station. The new lower reservoir can be built along the selected contour as shown in Figure 3. The second option would be for a PSPP is an expansion project on Victoria. The existing Victoria and the Randenigala Reservoirs can be selected as the upper and lower reservoirs for PSPP. Thirdly, the new PSPP can be an expansion of Laxapana Power Station. The Canyon pond and the Laxapana pond can be selected as the upper and lower reservoirs respectively. Finally the Kotmale also considered.

Figure 3 – New Lower Reservoir in Polpitiya

4. Transmission System Analysis

The entire transmission system of Sri Lanka in 2016 with the predicted load demand and generation pattern was modelled using the IPSA software. A comparative analysis of four separate interconnections of the newly selected PSPP was completed under night and day peak operating conditions as mentioned in section 2. The suitability of these two conditions for this study is detailed below.

It is generally known that the thermal power plants continuously operate at their most efficient capacity throughout the day [12]. Therefore, with the completion of large scale coal power plants in 2016 the excess generation than the base load can be efficiently used to pump water to the above reservoir of the new PSPP, during light loading conditions. Then the PSPP is able to generate power during the night peak time which will make the system economical as it minimizes the expensive peaking power generation in the grid [11]. Throughout the study the Kotmale generator unit 1 was maintained as the slack bus to have a common system and simplicity of comparing the results. Furthermore, three generating units with same capacity were introduced in the new power plant with the selected optimum capacity.

The optimum capacity has been obtained by building the network without interrupting the load demand. Earlier generation pattern was withheld and any overloading conditions or system outages were cautiously avoided. The optimum capacities of the new PSPP for the selected interconnections are tabulated in Table 1.

Table 1 – Optimum Capacity of PSPP

Interconnected Bus Bar	Optimum Capacity/MW
Polpitiya 220kV	3x 135 - 3x 150
Victoria 220kV	3x 160 - 3x 175
Laxapana 132kV	3x 135 - 3x 155
Kotmale 220kV	3x 135 - 3x 150

4.1 Load Flow Analysis

Load flow analysis under normal operating conditions was carried out to ensure the adequacy of the generation supply to the load demand and the losses. By incorporating the above mentioned new circuit on system loading, the effects on the circuit due to the rearrangement of the existing circuit has been investigated. The effects are exceeding of bus bar voltages, optimum system running conditions in terms of setting generations, reduce the system losses and minimize the changes required on rating of transformers. Before carrying out the load flow study, essential parameters were specified. The common base value for the transmission line equipment was taken as 100 MVA comparing different parameters in per unit values. The maximum number of iterations undertaken during a load flow analysis was 50 with the convergence accuracy of 0.1 MVA.

In the initial forecast of load flow study, when an overloaded grid substation is identified, three mitigatory measures were taken as usually followed by the CEB. Initially the excess load can be transferred to the nearest grid substation or the capacity of the grid substation could be enhanced. The augmentation was achieved by introducing a transformer with a standard normal capacity of 31.5 MVA. In the event of the failure of these two options, a new grid substation could be introduced to the existing system.

For example the load flow study on Kotmale 220kV interconnection, convergence was achieved with 15 overloaded grid substations namely, Kotugoda, Oruwella, Pannipitiya, Biyagama, Ratmalana, Kolonnava, Panadura, Dehivala, Jayawardanapura, Bolawattha, Veyangoda, Rathnapura, Galle, Matugama, Horana and Kurunegala. These overloading conditions were removed by following the above mentioned conventional methodology with the use of the possible optimum solution respective to each case. Finally a fully converged system was obtained for further examination.

Converged system with the new PSPP supplies the full capacity of its power to the whole transmission network. It has been noted that during the light loading conditions, due to evaporation losses from the exposed water surface and mechanical efficiency losses during conversion, only 70% to 85% [16] of the electrical energy used to pump the water into the elevated reservoir can be regained. The operation of PSPP, especially the maximum allowable power absorption during the light loading conditions was selected according to this criteria (i.e. pumping water to the upper reservoir).

The permitted voltage deviation at any bus bar of the network under normal operating conditions is 5% and 10 % for a 220kV and 132kV system respectively [13]. For each interconnection, voltage stability of the system was clarified where voltage exceptions were observed in bus bars during the load flow calculations. The voltage stability of the power system is directly related to voltages on system bus bars. With the reactive power injection, the voltage was not allowed to decrease as it may lead to an unstable system. Table 2 shows some voltage violations in the bus bars when PSPP is connected at the Kotmale 220kV bus bar. Similarly all voltage violations have been studied for all other three interconnections.

Voltage violations were removed by installing Mechanically Switched Capacitors (MSC) in affected locations. As the Polpitiya 220 kV interconnection has reduced number of violations, it reduces the number of MSCs to be installed, also resulting in reduced cost.

Table 2 - Violated Voltages at Bus Bars in Kotmale 220kV Interconnection

Bus Bars	Voltage/ p.u.
Fort 132 kV	0.799
Kurunegala 132kV	0.800
Anuradapura new 132kV	0.798
Maho 33kV	0.795
Vavunya 132 kV	0.741
Oruwela 132 kV	0.795
Kolonnawa 132kV	0.797

It was noticed that the voltage rating exception of the branch from Galle 132kV bus bar to Galle 33 kV bus bar cannot be removed. Therefore, throughout the analysis, the SVC in Galle has been maintained as switched off.

After obtaining a converged system, the voltage magnitudes of some selected bus bars are represented in Table 3. The total power loss of the entire network has been obtained and compared. The results are tabulated in Table 4.

Table 3 - Details of Important Bus Bars for Kotmale 220 kV Interconnection

Bus Bars	Voltage Magnitude
Pannipitiya 220kV	0.963
Biyagama 220kV	0.955
Anuradapura 220kV	0.890
Victoria 220kV	0.993
Kotmale 220kV	0.983

Table 4 – Power Loss of the Entire Network for Each Interconnection

Inter-connected Bus Bar	Selected Capacity/ MW	Used Capacity/ MW	Power Loss/ MW
Polpitiya 220kV	3x150	3x150	199.598
Victoria 220kV	3x175	3x150	210.433
Laxapana 132kV	3x155	3x150	206.957
Kotmale 220kV	3x150	3x150	202.089

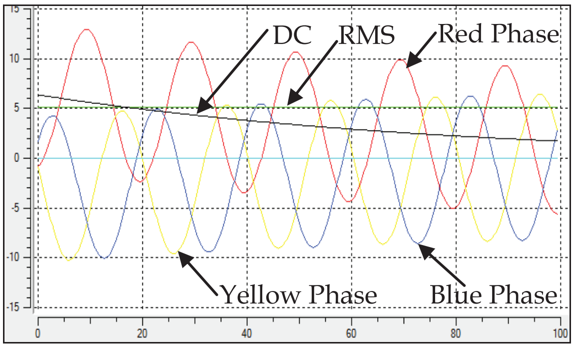
Transmission losses in each network under several conditions have been calculated by considering the readings of total generation of the network and the total loads. Here, the Polpitiya 220kV interconnection shows reduced transmission losses. The rating of 450MW for each interconnection was assumed during the calculation of losses under the same condition as in table 4.

4.2 Fault Level Analysis

IPSA fault calculations were performed using a special method called "the standard IPSA +" method and calculated if the fault flows down branches or forms fault waveforms. The balanced and unbalanced faults were studied. Before the fault calculations, it was made sure that the following conditions were met. The network with flat voltage profile was unloaded, shunt components or branch susceptance was removed; the transformers were kept at their

nominal tap positions; the voltage and impedance correction factors were ignored.
This special type of study is considered only in the case of a three phase line-line-line symmetric fault with a fault time of 100ms, a maximum iteration of 5, having zero fault impedance and that the maximum asymmetry occurs in the red phase.

The fault level calculations were done at extreme conditions of night peak. Some important lines were taken into consideration where faults may occur frequently and the results were compared using graphical representation and tabulations.



Fault current (pu) Vs time (ms)

Figure 4 - Fault Currents obtained during the fault study at Polpitiya 220kV Interconnection

Fault level results were obtained for all interconnections. Results were according to the effects of external network impedances and other neighbouring machines which adjust the fault contributions and decay time constant. Figure 4 shows an example of fault current waveform that was obtained when the line connecting Polpitiya 220kV Bus Bar and the New PSPP Bus Bar, was faulted

Table 5 shows the peak fault currents when the Interconnection bus bar, was faulted. Out of the four different interconnections the fault level at Polpitiya 220kV bus bar was the lowest.

Table 5 - Comparison of Fault Currents

Interconnection Bus Bar	Fault Level/kA
Polpitiya 220kV	23.1
Victoria 220kV	23.4
Laxapana 132kV	36.2
Kotmale 220kV	32.7

5. Transient Stability Study

The transient stability study was conducted to simulate the dynamic response of an electrical power system under fault or machine and branch switching disturbances using the step-by-step method. Initially the load flow study was carried out. Mainly the load flow solution is used as the initial system conditions for other studies. In this study lines, transformers or shunt in the system was set to switch to introduce transients.

A shunt was introduced where the transient fault is specified. The shunt was set to a status of "Disconnected, switched during Transient". The shunt reactance, which was the fault impedance, set to a negligible value to make solid ground fault. The times at which the fault is applied and cleared are specified according to the CEB long term transmission planning report 2008. During the study the transmission system was subject to specific pre-identified transient system disturbances which are expected to be critical.

Studies were carried-out under two switching sequences as given below.

1) Successful re-closing: t=0 Fault occurs
   t=120ms fault cleared and circuit tripped
   t=620ms circuit re-closed
2) Unsuccessful re-closing: t=0 fault occurs
   t=120ms circuit tripped
   t=620ms circuit re-closed with fault
   t=740ms circuit tripped

Throughout the study the study-length was taken to be 1 second and the Kotmale generator (generator with the slack bus) was selected as the reference generator. The maximum step length of the study was selected as 10ms. Voltage magnitude, frequency variation and rotor angle variations of affected bus bars were obtained and the stability of the system was examined.
Extreme case of night peak condition has been studied. The bus bar voltages were initially steady. When the transient fault occur, the voltages dramatically dropped and when the fault is cleared again there was a sharp rise.

5.1 Dynamic Simulation for Transients

The dynamic studies were completed and the results are as displayed in figures 5 and 6 with the stability diagrams. The results were checked especially for the three generating units which were proposed to be installed in the new PSPP.
Eg 1: Three phase short circuit fault on one of the 220kV overhead line between new PSPP and Polpitiya Power Station at Polpitiya end, assuming successful re-closing is shown in Figures 5

Eg 2: Three phase short circuit fault on one of the 220kV overhead lines between new PSPP and Polpitiya Power Station at Polpitiya end, assuming unsuccessful re-closing is shown in Figures 6

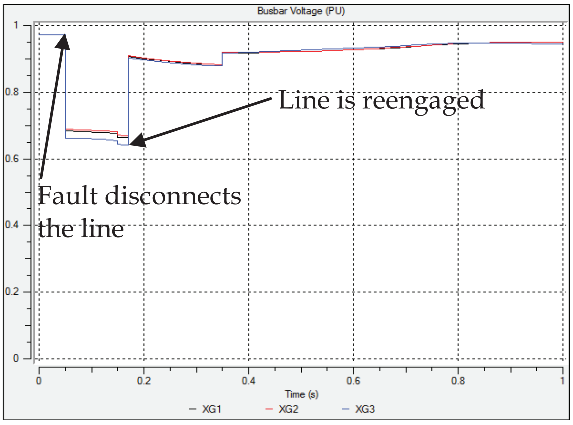


Figure 5 – Variation of Busbar Voltage with Time when successful re-closing

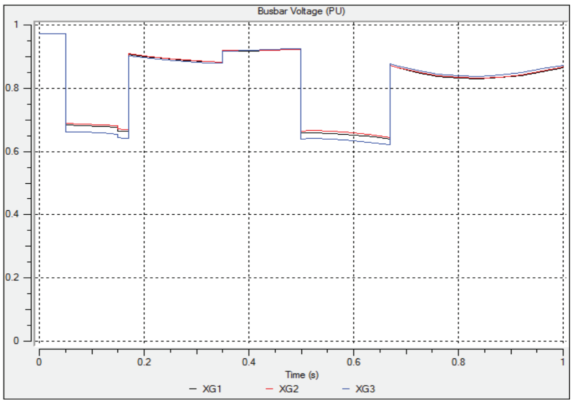


Figure 6 – Variation of Busbar voltage with Time when unsuccessful re-closing

Due to this above transient some of the lines were switched out as a result of load shedding. The disconnection of lines or the remarkable changes that took place in the system within the observed five seconds are provided below.

One of the automatic line disconnection during the transient study was "Line of impedance [0.0256 + 0.1304j] switched out between buses Kotmale_220 and Habarana_220 at time 4.4s. It results on further disconnection of lines if the fault is not cleared at limited time.

Interconnection Bus Bar	Bus bar voltage/p.u.
Polpitiya 220kV	0.6027
Victoria 220kV	0.6149
Laxapana 132kV	0.5779
Kotmale 220kV	0.6753

Simulation results obtained, as shown in Figures 5 and 6, for each of the four possible interconnections were similar. Therefore a comparison of new PSPP busbar voltage during the transient conditions at 0.12 second, which is during the fault, is illustrated in table-6.

6. Summary and Conclusion

Overall, the interconnection of PSPP was studied with suitable sites such as Kotmale, Victoria, Polpitiya and Laxapana. From this study the promising three sites are Polpitiya new Power Plant, an expansion project of Victoria and expansion of Laxapana Power Plant.

The Polpitiya new candidate power plant would be the most suitable for the transmission system because the Polpitiya interconnection showed better results throughout the technical analysis compared to others. But a more detailed feasibility study on the selected site must be carried out. Secondly the Victoria expansion project can be selected where either Victoria 220kV or even Kotmale 220kV bus bar interconnections are also show good results. Thirdly, the interconnection of the new PSPP is also possible at the Laxpana 132kV or even the Polpitiya 220kV along with the expansion project of Laxapana power station.

Finally, this analysis and site selection provides an overview for the designers of PSPP, engineers and policy makers to analyse further in selecting the best site and the appropriate transmission interconnection. Implementation of such a power plant in Sri Lanka and the proper interconnection would yield improved electricity system network especially during peaking hours while making use of excess generation during the light load operation.

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Annex 1

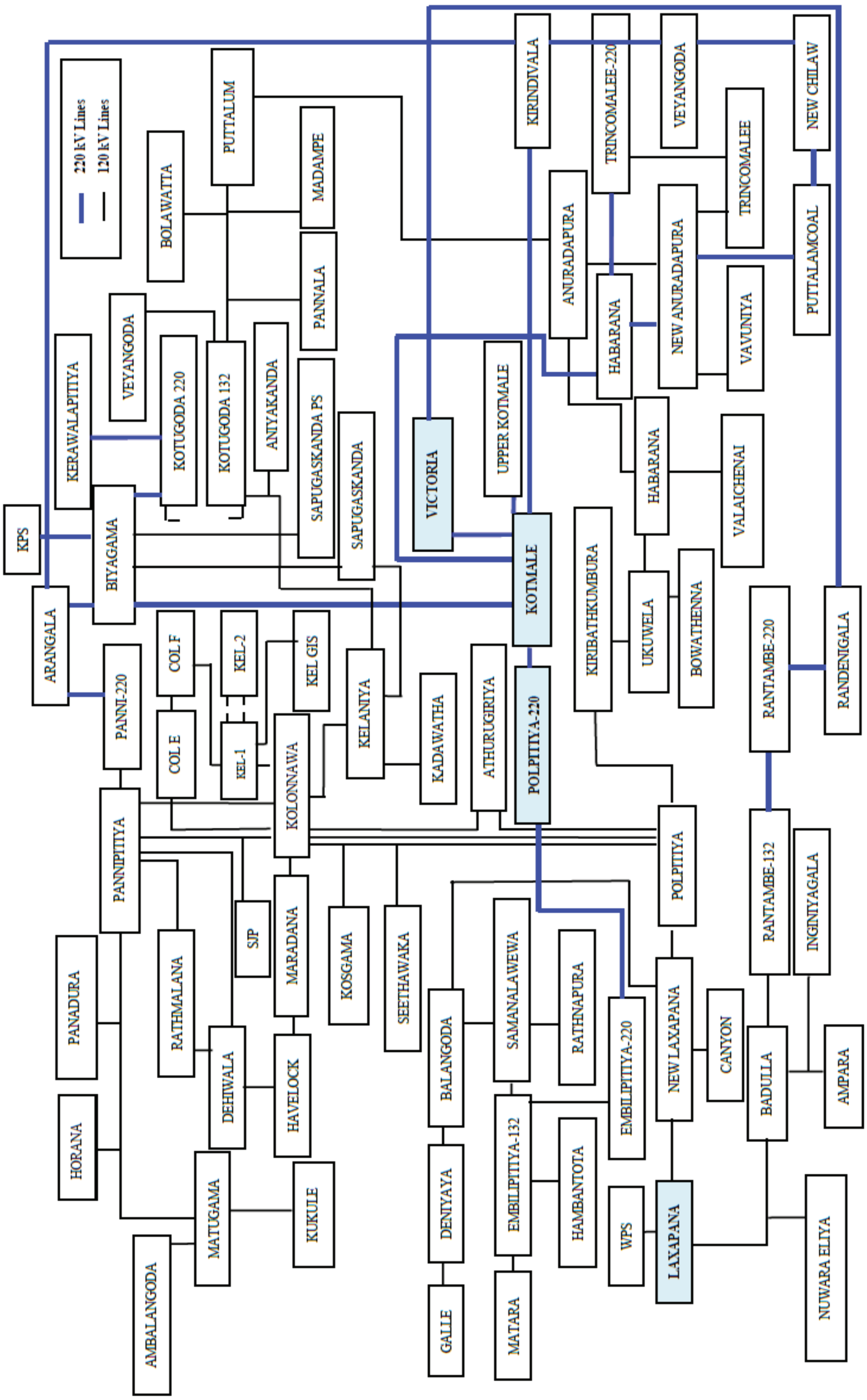

Figure 7 – Sri Lankan Transmission Network as in 2016