Generation Cost Optimization through a Network Stability Study – Final Report –

Dr. L. N. Widanagama Arachchige

Prof. J. R. Lucas

Ms. M. S. Nakandala

Department of Electrical Engineering

University of Moratuwa

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Contents

1 Background

1.1 Sri Lanka National Grid

The Ceylon Electricity Board (CEB) and Independent Power Producers (IPP) generate electricity in Sri Lanka, using hydropower and petroleum fuels. The power system is also supported through many renewable energy projects. Power transmission in Sri Lanka is operated by CEB under 132 kV and 220 kV voltage levels. Both CEB and Lanka Electricity Company (LECO) distribute electricity. The distribution voltages are 33 kV and 11 kV at medium voltage and 400 V at low voltage.

As is the early days, the growing energy demand cannot be completely supplied by hydro power plants and all forms of electricity generation have been evaluated and reviewed to determine the economic feasibility of generation. Fig. 1 presents the fuel consumption and cost for thermal power generation in Sri Lanka for the years 2012 and 2013 [1]. It is clear that the long term bulk electricity requirements would have to be fulfilled by coal power plants, nuclear power plants and perhaps liquid natural gas (LNG) as they have the lowest cost of production per unit of electricity. However, at present there are no nuclear or LNG plants being envisaged in the long term generation plan. The total electricity generation in Sri Lanka, as of June 2014 is 6086 GWh and Fig. 2 presents the energy mix where nearly 24% of electricity is coming from coal power.

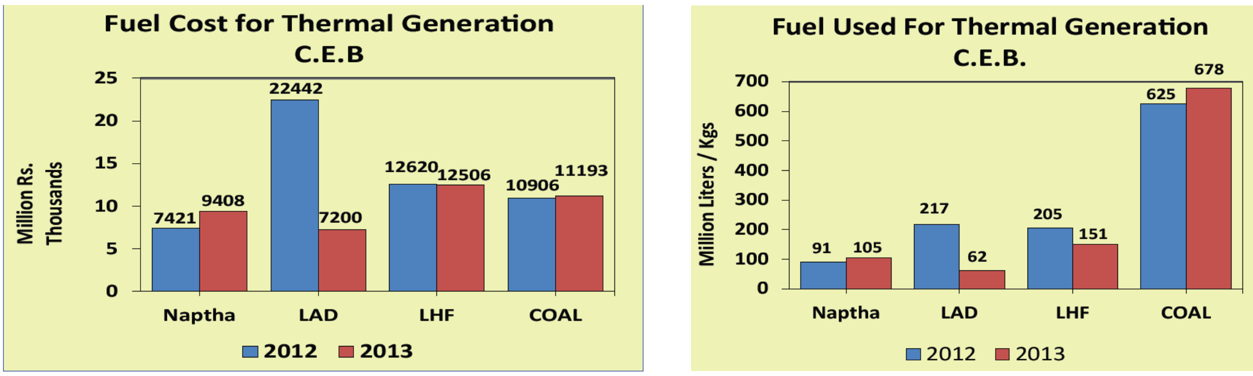

Fig. 1 Fuel Consumption and Cost for Thermal Generation [1]

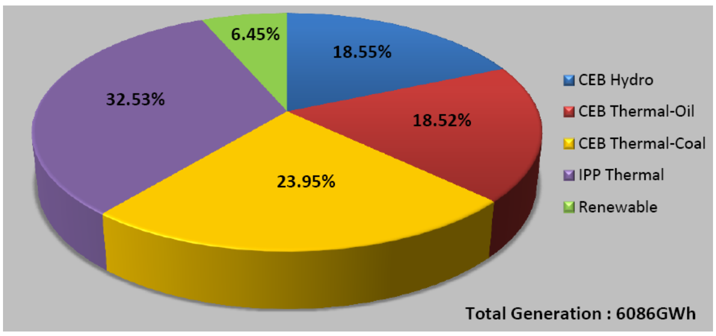

Fig. 2 Energy mix as of June 2014 [2]

By June 2014, the Puttalam Coal Power Station capacity was 600 MW and by 2015 with the completion of Phase III its total generation capacity is 900 MW. However, there are constraints imposed on the utilization of the generation resources by the standards and the practices. Even though the size of the plant is increased, the plant cannot always be fully utilized and this leads to underutilization of the generation plants in the system. For instance, issues arise in a power system network when large generators trip from the system. Thus, the CEB has limited the running capacity of the largest generator to 20-30 % of the demand at any given time. However, it is important to verify such capacity limitations by conducting detailed stability studies.

1.2 Power System Stability

Fig.3 presents the country's daily load curve recorded on the day of annual peak for years 2007 to 2014. It shows that the shape of the load curve has not changed much for the given years and the system peak demand occurred from about 19.00 to 22.00 hours daily. The recorded maximum system peak is 2,164MW in year 2013. As in Fig.3 the off-peak demand in 2014 is about 1000 MW. Therefore, the maximum output of a single generator would be 300 MW if limitation of 30% maximum generation loading of the total demand is imposed.

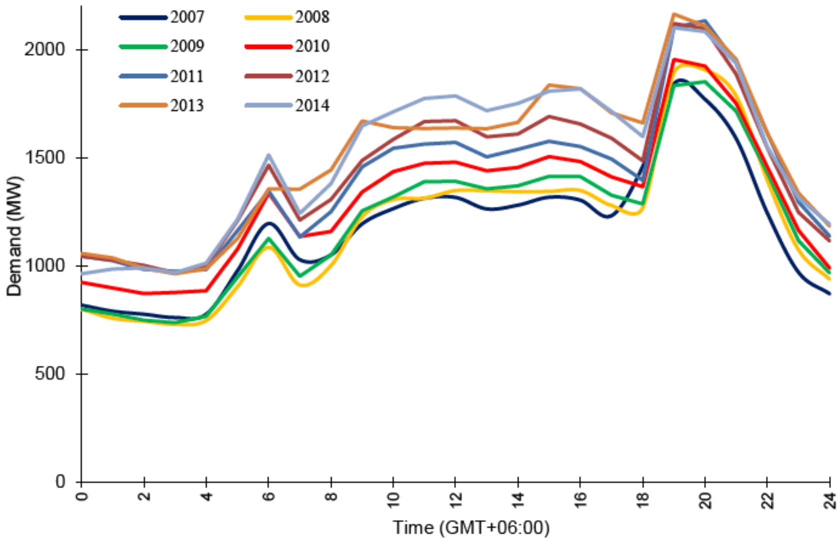

Fig. 3 Change in daily load curve over 2007 to 2014 [3]

The single contingency is a minimum standard used in operating of a power system, which means the loss of a single element (Generator or transmission line) should not affect the supply to any consumer within the system. In Sri Lanka it is mainly applied to the transmission system. Theoretically, the spinning reserves which a power system needs to maintain should be the size of the single largest generator unit, such that the tripping of that could be recovered. If the Sri Lankan situation is taken into account the largest generator unit capacity needs to be 30% or less of the demand at any given moment of time. So ideally Sri Lanka would need a spinning reserve of about 30%, but as maintaining spinning reserve is expensive it is kept at a lower value. Therefore, when spinning reserves are lower than the largest generator unit, load shedding is used such that the system stability could be maintained.

The present Load shedding scheme is shown in Table I. The load shedding is initiated through a rate of change of frequency (df/dt) value. If the frequency falling rate is less than 0.85 Hz/s, 7.5% of total load is shed when frequency drops below 48.75 Hz for 100 ms. If the frequency does not build up, an additional 7.5% of total load is shed in the second stage when frequency drops below 48.5 Hz for 500 ms. In the third and fourth stages additional 11% of total load each would be shed at frequencies of 48.25 Hz and 48 Hz respectively if frequency stays below said levels for more than 500 ms. In the fifth stage further 10% of total load would be shed at 47.5 Hz instantaneously, bringing the total load shed percentage to 47% of the total load. In the event of a large loss of a generator, the rate of change of frequency becomes high. The configuration for that in the present load shedding scheme is such that if df/dt of -0.85 Hz/s is detected and if the frequency falls to 49 Hz, it would shed 18% of the total load.

Table I: Under Frequency load Shedding Scheme of CEB as of December 2015 [4]

Stage	Load Shedding Criteria	Load per Stage	Reconnection Criteria	Reconnecting Load
I	48.75 Hz + 100 ms	7.50%		
II	48.50 Hz + 500 ms	7.50%		
III	48.25 Hz + 500 ms	11%	51 Hz + 500 ms AND df/dt > 0.2 Hz/s	2%
IV	48.00 Hz + 500 ms	11%	51 Hz + 500 ms AND df/dt > 0.2 Hz/s	2%
V	47.5 Hz instantaneous	5.50%		
	47.5 Hz instantaneous **OR** 49 Hz AND df/dt < -0.85 Hz/s + 100 ms	4.50%		
df/dt	49 Hz AND df/dt < -0.85 Hz/s + 100 ms	13.5 % and 4.5% embedded in V		
Total	df/dt	18 % (4.5 % embedded with V)		
	Frequency only	42.50%		

Since the introduction of large 300 MW Coal Power Plants to the Sri Lankan system, although it is a cheap resource, it had been necessary to limit the utilization of the coal plant during off-peak hours due to the 20% loading limitation practiced earlier in the county. This practice led to increase the system running cost due to the underutilization of the Puttalam Coal Plant. Now, the loading limitation has been increased while there is an addition of stage 2 and stage 3 of the Puttalam Coal Plant bringing it to 900 MW total capacity. Although one unit could be loaded to perhaps 30% of the total system demand, there was only one double circuit line which brought down power from the Puttalam Coal Plant till the new line to Anuradhapura came in 2015. With these system changes there is a necessity in doing a stability study to determine the optimum utilization of the cheap coal power resource. There is research being conducted to increase the utilization of power resources and hence increase the efficiency of the system through load shedding schemes. Both under voltage load shedding (UVLS) and under frequency load shedding (UFLS) methodologies are being practiced worldwide.

An optimal under voltage load shedding design is evaluated in [5]. The paper discusses about the important factors in the load shedding algorithm such as load shedding steps, amount of load that should be shed in each step, the delay between the stages and the location of load shedding. They have proposed a static load shedding, which sheds a constant load at each step and dynamic load shedding scheme, which the load will be determined according to the magnitude of disturbance to achieve system stability. A similar approach is discussed in a recent study presented in [6]. It is also concluding the effectiveness of using dynamic load shedding to have an optimal solution in achieving system stability.

In [7], it is proposing to increase the single largest generator size up to 25% of the current demand for the Sri Lankan power system. Simulations are carried out by taking into account the worst case scenarios for the system and thus the system would react better at other generation mixes. The load shedding scheme is proposed to be revised by selecting the df/dt ratings such that large generator tripping is detected fast. It is concluded that, even with the largest generator loss, the system can achieve stability without going to a blackout. In [7] it has only considered 220 kV and 132 kV transmission network in building the power system model to conduct system stability simulations and the study is carried out considering the 2011 network. Considering the drastic system changes since 2011 to the present network, it is important to research on an optimum single unit capacity constrains based on system transient stability.

2 Objectives and Scope of work

The ultimate objective of this research is to find the optimal size of the single largest generator based on system transient stability criteria.

The specific objectives are;

- Development of a model to simulate the Sri Lankan Power System using transient analysis software to conduct simulation studies and achieve a stable model.
- Carry out the necessary stability studies to determine optimum utilization of generation during off-peak, while matching the system reliability criteria used by the CEB.
- Study and recommend improvements on the existing system operating standards related to loss of largest single generator unit size.
- Study and make recommendations for network augmentation to optimize the cost of generation especially during off-peak time.

3 Research Methodology

Modeling of the Sri Lankan power system will be carried out by using PSCAD/EMTDC, taking electromechanical transient aspects into consideration to determine system stability. Actual/typical system parameters are used in developing the simulation model. PSCAD (Power System Computer Aided Design) is the software which is being used in this project to simulate and test the near perfect national grid of Sri Lanka which is used to test and formulate a revised load shedding scheme. PSCAD is a GUI based on the engine Electromagnetic Transients including DC (EMTDC). This allows create, conduct and visualize power system behavior through simulations. Also it allows the display of instantaneous values of measurements and also allows changes in system parameters during the simulation. PSCAD has a rich library of elements ready for insertion into a test simulator. In addition to the simple passive components it also has comprehensive and complex models such as models of electric machines, overhead lines, cables, etc.

Considering the load curve, clearly different scenarios can be identified for simulation studies, such as: peak demand time period, the mid-day demand period or the off peak demand period. However, the generation limit of a single generator is critical during the off-peak demand. Therefore, this study is focused on simulating off-peak demand period. Actual power system recordings are used to validate the model and the developed model will be used to analyze system stability during the off peak period. The simulations will be carried out by selecting different contingencies in the system to find the optimal capacity for a single generation unit in the Sri Lankan power system.

The load shedding due to lower frequency or lower voltage detecting a large generator loss curtails amount of load in the power system until the available generation could supply the remained loads. Therefore it is vital to evaluate the load shedding schemes in use and make necessary recommendations for increasing the system reliability.

4 Power System Modeling

Simulation studies were carried out using PSCAD/EMTDC power system simulation software using a simulation time step of 10 μs. PSS/E software was used for power flow studies [8]. These are well established commercial software used in utilities and power system consultation agencies for power system simulation. Fig. 4 presents the power system of Sri Lanka, developed in PSCAD/EMTDC referring to the 2015 system given in the Long Term Transmission Development Plan, 2013 – 2022 of CEB [9]. Actual data corresponding to an off-peak loading was collected from the CEB, and PSS/E system was developed accordingly to do the load flow analysis. Load flow results are required to initialize the PSCAD model. The total load in the selected off-peak situation was 1052.5 MW and 432.2 kvar. The loads were simulated using the fixed load model in PSCAD, where it models the load characteristics as a function of voltage and frequency. Appendix A.1 presents the detailed information about the power system load distribution. Transmission system of the Sri Lankan power system in 2015 is shown in Fig. 5 and schematic diagram with line parameters are presented in Appendix A.2. Bergeron model was used in designing the power system transmission lines. The transmission line configuration and line parameters given in Fig. 5 and Appendix A.2 were used to model the system, and standard electrical parameters for different types of conductors were used accordingly to configure the line models.

Several criteria were considered in designing the generation stations, according to the applicable generator control strategies for different units, such as constant power, constant voltage generators, swing generators, renewable power plants and distributed generators. Total installed capacities of different types of power generation stations are given in Appendix A.3 [11]. In modeling the medium/ large generators, which are running as constant power, constant voltage units, governor, turbine and excitation units were properly incorporated to the synchronous machine models. Machine models were configured using the dynamic parameters including the inertia constant data received from the PUCSL. The data were clarified against the typical data given in [10]. In modeling the coal power station and other medium/ large thermal power stations, AC1A Exciter, Steam Gov 1 model and Steam_Tur_1 model were used as the exciter, governor and turbine respectively. Typical parameters [10] were used to configure the models. In modeling hydro generator stations in this category, Synchronous machine model, AC1A Exciter, Hydro Gov 1 model and Hydro Tur 1 model with appropriate configurations were used respectively as the generator, exciter, governor and turbine models. These machines were run in droop control with the droop setting at 0.04 pu. Gas turbine driven generators and diesel generators are not operating during the off-peak period and they were not simulated. In the design, Victoria power station is running as the swing generator, who is responsible for frequency control. It is also modeled using the synchronous machine model, AC1A Exciter, Hydro Gov 1 model and the Hydro Tur 1 model with typical parameters. In the frequency control operation, generators are running in a lover droop and thus, the droop setting of this governor was set to 0.02 pu.

In general, medium/ small renewable power stations like wind power plants and distributed generators like mini-hydro plants are considered as negative loads in the system under steady state analysis. In modeling these power stations for this stability study, the synchronous machine model, AC1A Exciter and a constant torque input was used. Complex dynamic controls in wind power stations were not modeled considering the fact that transient scenario of interest in this study is in several seconds to minutes in time.

The current load shedding scheme of Sri Lanka power system given in Table I was also implanted in the model. It is an under-frequency static load shedding scheme and the shedding of load feeders under each load shedding stage were selected according to the practice in actual power system, where the selection is based on a priority scheme.

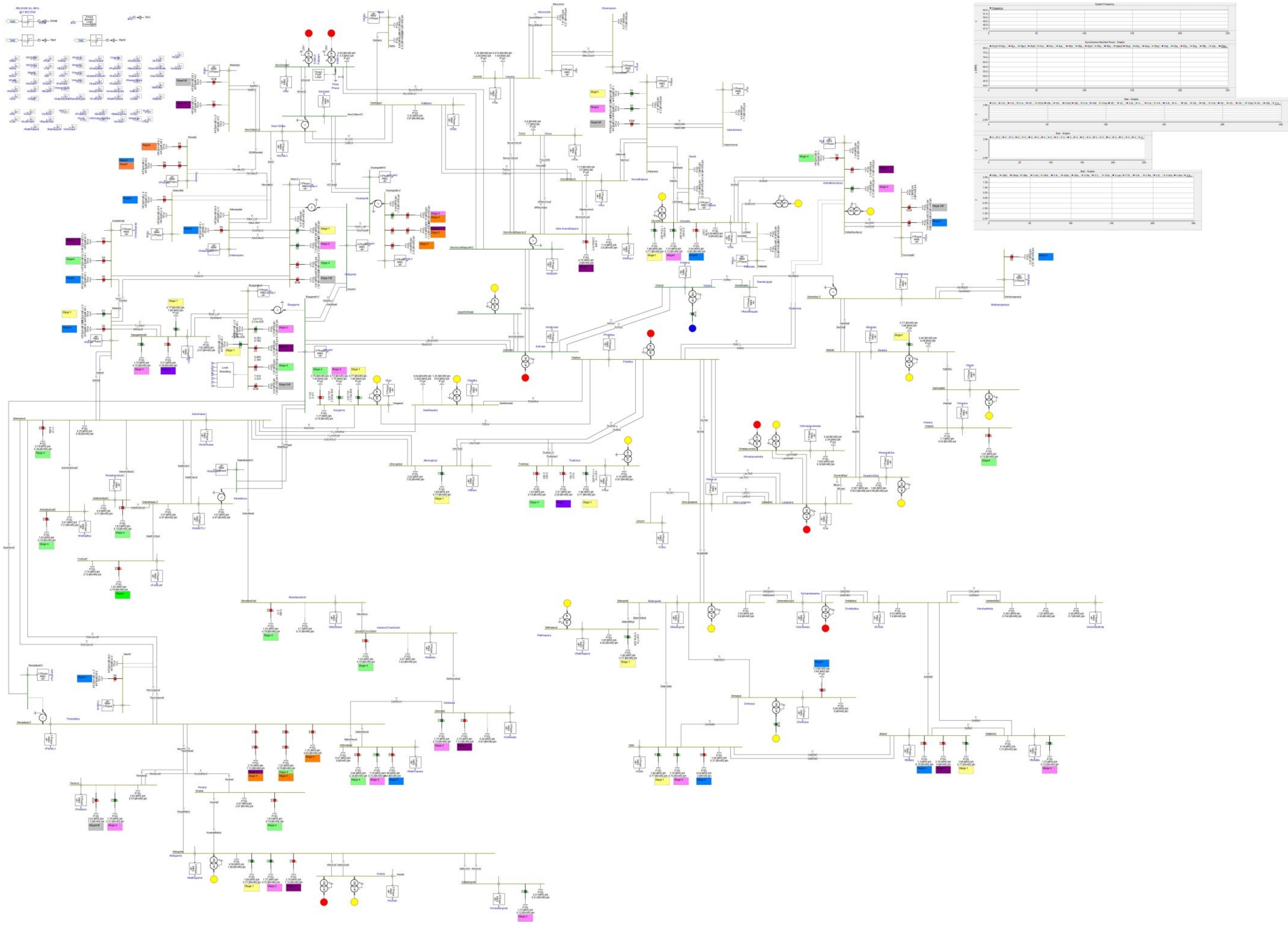

Fig. 4 Developed PSCAD modeled of the 2015 Sri Lankan power system

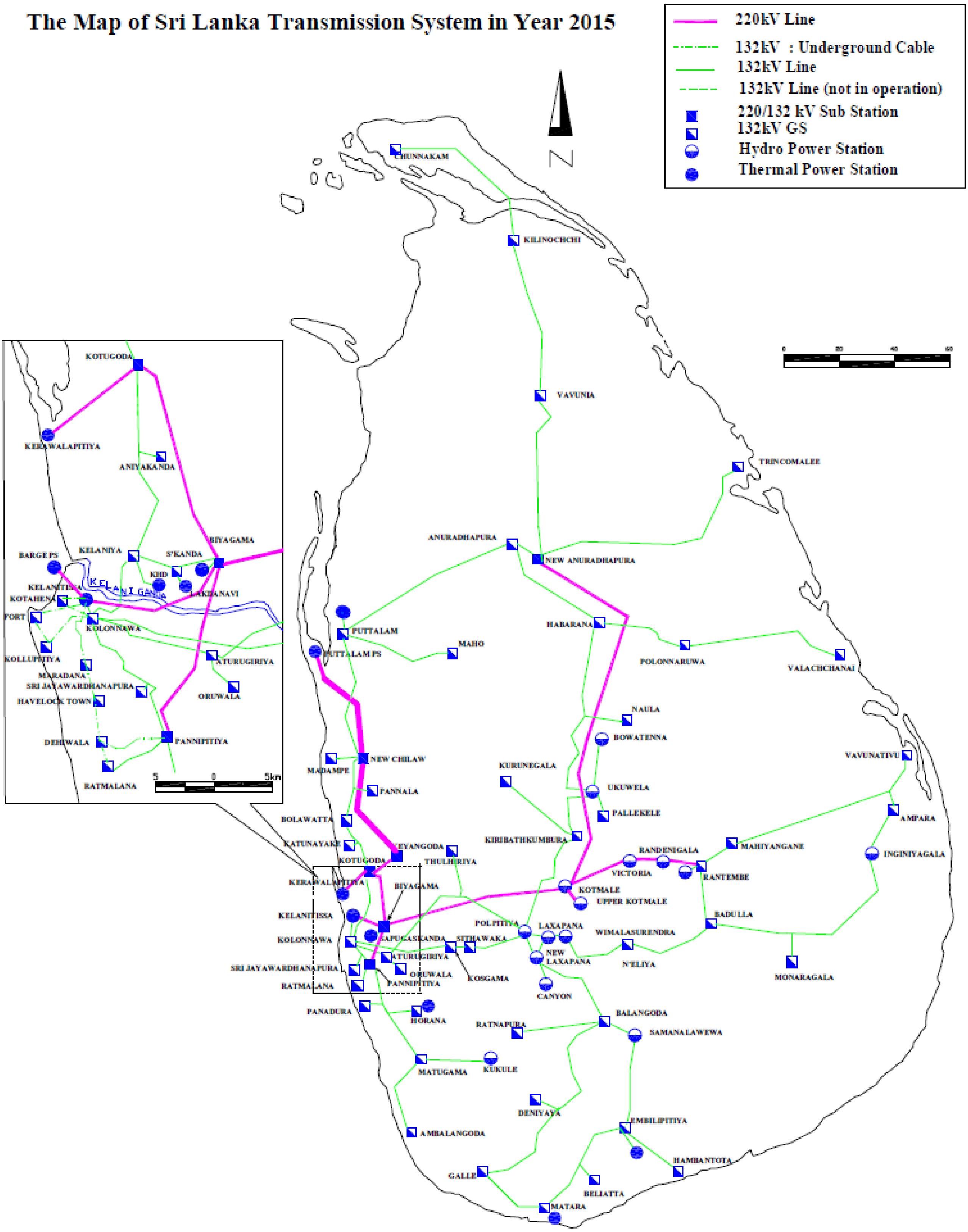

Fig. 5 Map of Sri Lankan power system in 2015 [9]

5 Simulation Results and Discussion

5.1 Model Validation

The first step before dong a complete transient stability analysis of the system is to validate the model developed. This is very important in the context that Sri Lankan power system data are not quite often available in a form required for transient analysis.

The developed power system model gives stable operation under different power system contingencies like faults and large generator tripping.

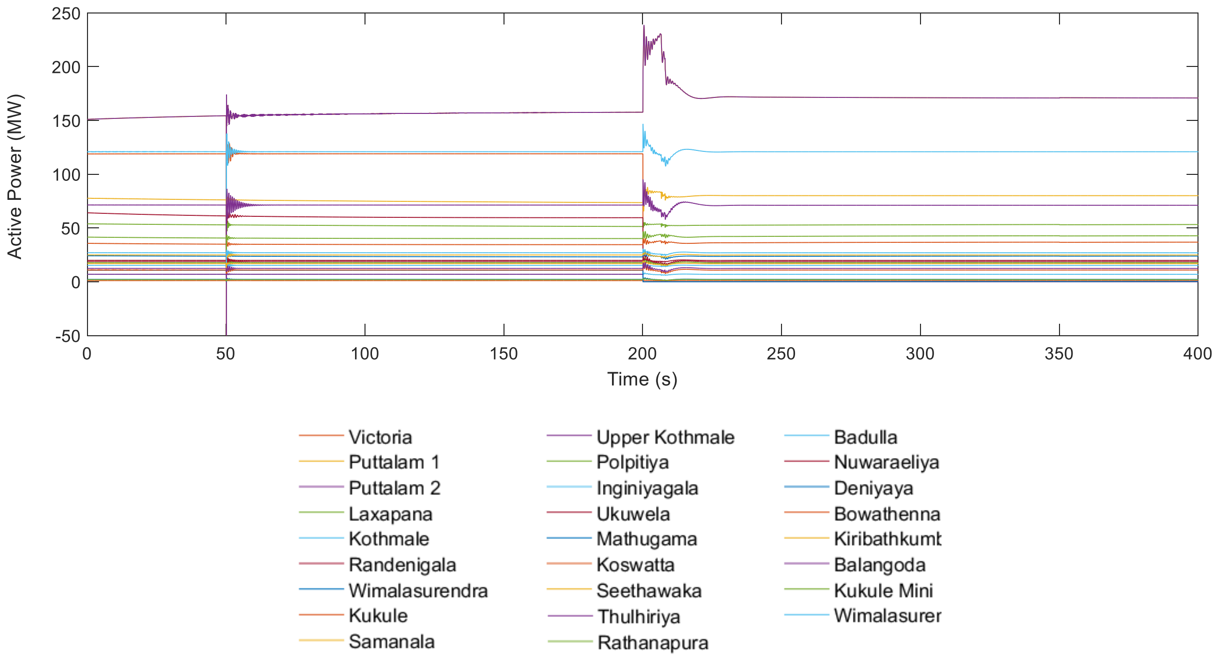

Fig. 6 Power output of connected generation stations

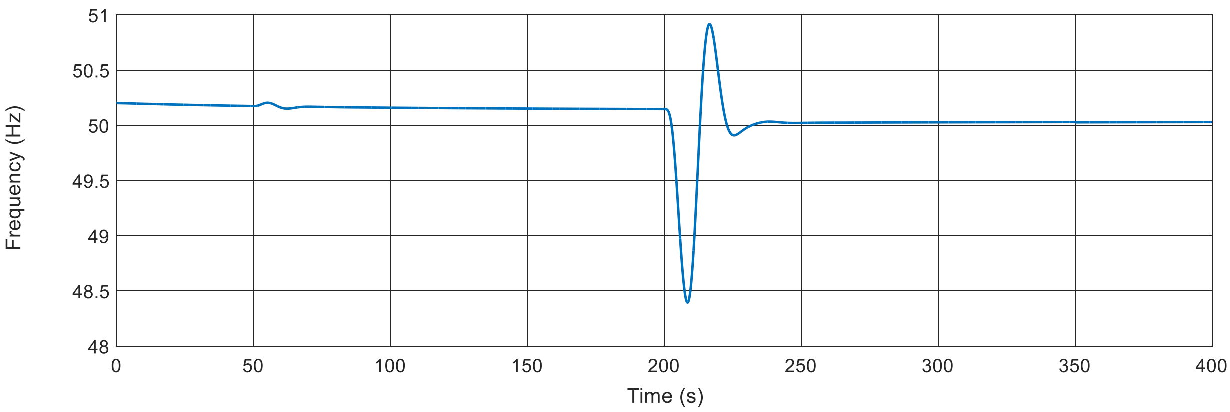

Fig. 7 System frequency response

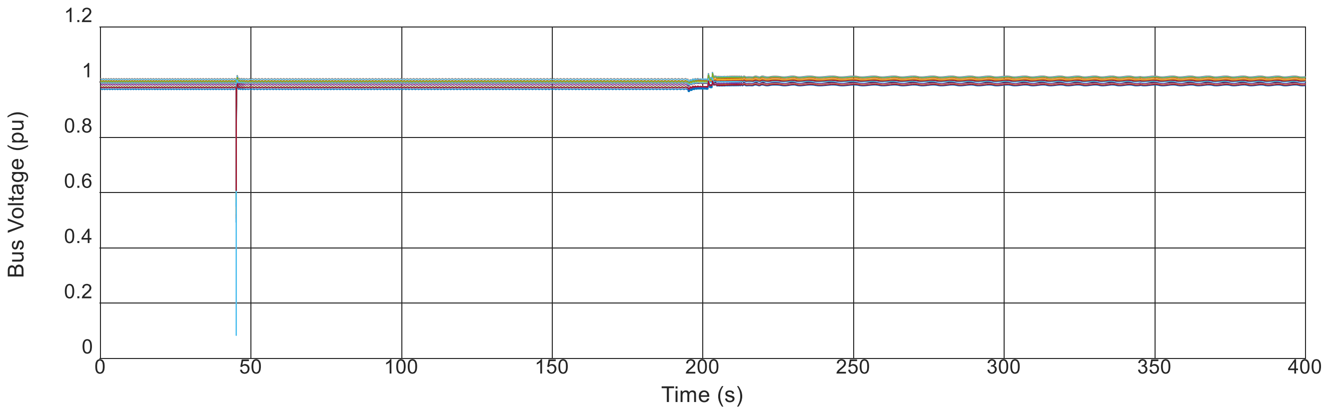

Fig. 8 Busbar voltage response

Fig. 6, Fig. 7 and Fig. 8 respectively present the active power outputs of all the connected generator units, system frequency response and bus voltages under a three-phase temporary, solid fault at 50 s and tripping of large generator units at 200 s. These simulations were carried out with only two phases of the coal power plant in operation at Puttalam, each at 155 MW and the Victoria and Randenigala hydropower plants were generating 120 MW and 61 MW respectively. The total load in the selected off-peak situation was 1052.5 MW and 432.2 kvar.

At 50 s of the simulation time a three-phase temporary, solid fault was created at the Norochcholai, Puttalam busbar. Figs. 6, 7 and 8 present that the system experiences a transient during the fault, but it is capable of re-establishing stability when the fault is cleared. The three phase bolted fault was given at the Puttalam bus bar and the highest transient observable in the bus voltages given in Fig. 8 is at the Puttalam Busbar. Also, Fig. 8 indicates that voltages are maintained within the ±1% specified limits in the standards for normal operation.

At 200 s of the simulation time both Victoria and Randenigala power stations were tripped off from the system. With the decaying of frequency, load shedding scheme was initiated and the results show that the load shedding stages stage-I and stage-II were activated respectively at 256.65 s and 258.05 s to stabilize the frequency. Prior to the activation of the load shedding scheme, there is an increase in the generator power outputs due to the generator inertia. The total load at the time of generation loss was 1052.5 MW and 432.2 kvar and the total active power generation at that time was 1070 MW. The total generation loss was 181 MW giving 17% loss of generation from the total. With the shedding of the loads, the system stabilized at a new operating point and the generator power outputs have changed accordingly.

These results rationalize the stable operation of the developed detailed power system model of Sri Lanka. A simulation run time of 400 s is presented here to emphasize the stable operation of the developed power system model.

In order to validate the developed power system model, simulated results were compared against the actual data. Fig. 9 presents the comparison of frequency responses of actual and simulated power systems at a loss of generation in off-peak loading.

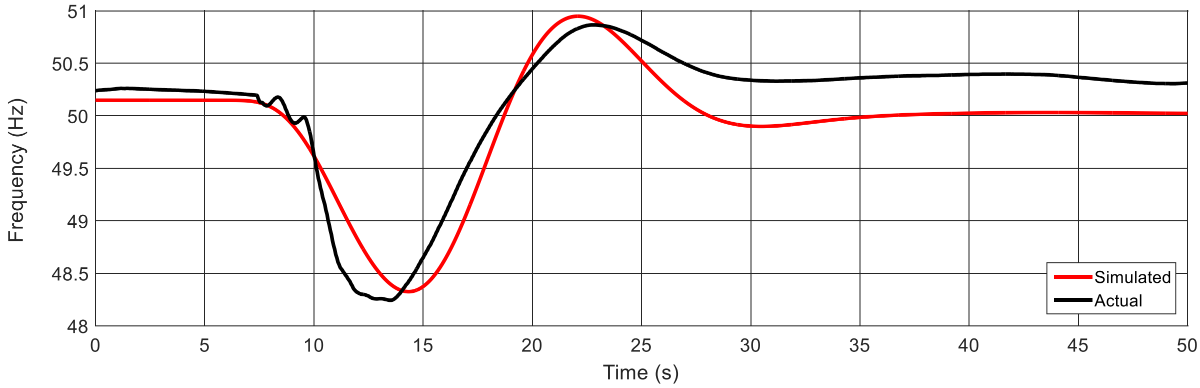

Fig. 9 Comparison of frequency responses of actual and simulated power systems at a loss of generation in off-peak loading.

The simulation of generation loss in this study was created considering a similar situation occurred in the Sri Lanka power system on 6th December 2015. In collecting actual data there are limitations in finding the load flow results just before the contingency. Therefore, power system validation considers a similar situation than simulation of the exact conditions. Actual data gives loss of generation at an off-peak time (10:12 am) on 6th December 2015. Actual load shedding data received indicates that Victoria, Randenigala and Rantembe generation stations had tripped totaling 181 MW when the total generation was 1054 MW in the actual system indicating 17% loss of generation. However, actual 30 min generator loading data indicates that at the time of tripping, Victoria plant was delivering 120 MW, Randenigala was delivering 61 MW, Rantembe was delivering 52 MW totaling a 233 MW giving 22% of generation. Therefore, in order to match with the percentage loss with actual available load shedding information, simulation was carried out considering the tripping of Victoria and Randenigala power plants totaling 181 MW giving 17% loss.

The frequency response of the simulated power system at the generation loss matches very closely with the frequency response of the actual power system at a loss of power generation with the load shedding taking place. There are several reasons for not getting the exact responses in the two systems, which can be discussed as follows:

1. Although the total system loads closely match in the simulated and actual power systems, the power flow in the simulated system is not exactly the same as the actual system when the generators were tripped off. Feeder loading and generator loading are different in the two systems.
2. Percentage loss of generation may be different in the simulated power system compared to that of the actual power system even though recorded information is considered. It is possible that embedded generators being tripped with the transients in voltage waveforms (through the vector shift relay) at the tripping of large generators. This can increase the percentage loss of generation, which in turn increases the rate of change of frequency.
3. When the feeder loading is different in each case, the amounts of loads shed at each load shedding stage in the two cases are different.
4. All the loads in the simulated power system are modeled using the fixed load model in PSCAD, where it models the load characteristics as a function of voltage and frequency. In the actual power system, there are various types of loads with various electro mechanical and electromagnetic characteristics, which are not counted in the simulation.

With the validation of the developed power system, its robustness under different load flow scenarios was tested. Fig. 10 presents the power outputs of selected major generators and Fig. 11

presents the system frequency response when one of the phases out of the three Puttalam coal power plants was tripped. Each of the coal power plants was generating 190 MW of power and Victoria Power station was generating only 14.4 MW of power prior to the tripping of the coal power plants. Although generation at Puttalam and Victoria power stations were changed and few generation stations were added, the total load in the selected off-peak situation was not changed and it was 1052.5 MW and 432.2 kvar.

Figs. 10 and 11 clearly indicate that the simulated power system comes to a stable operating point after facing a major generation loss and load shedding. Therefore, the developed simulation model of Sri Lankan power system can be effectively used for stability studies under different load flows and different contingencies.

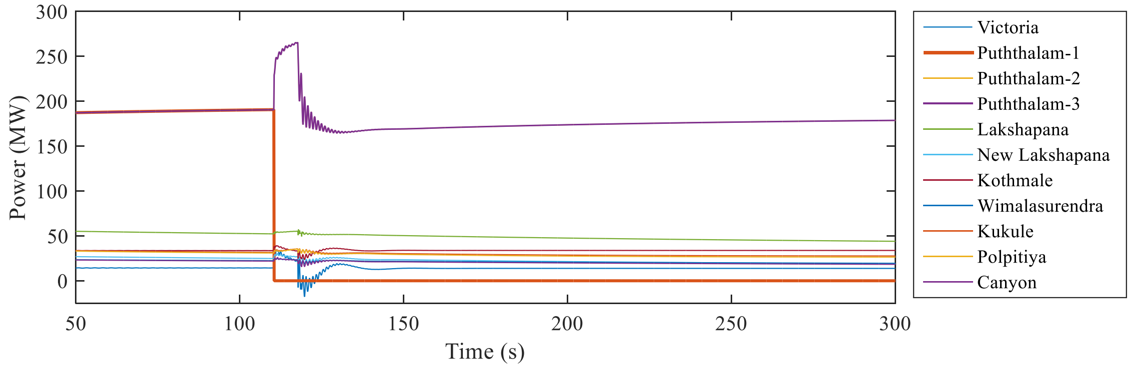

Fig. 10 Power outputs of major generators at the loss of 190 MW loaded Puttalam coal power plant.

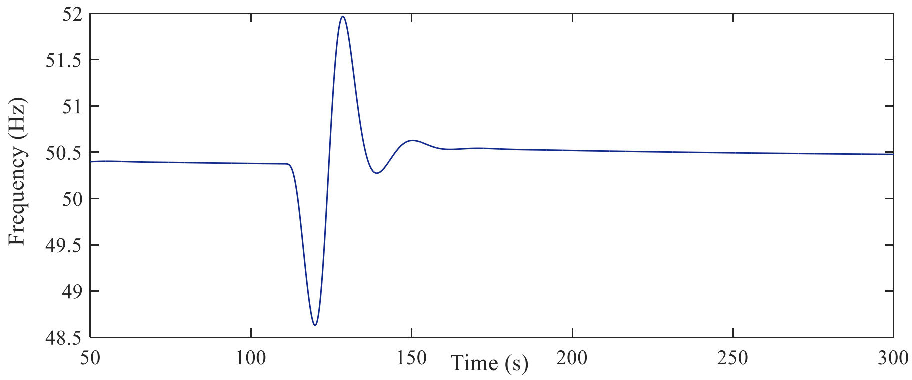

Fig. 11 System frequency response at the loss of 190 MW loaded Puttalam coal power plant.

5.2 Load Shedding Scheme

5.2.1 Weaknesses of the Present Scheme

The present load shedding scheme given in Table I indicates that total load shed can be 60.5% of the total load. This load shedding scheme is designed for more than 100% overloading. It can be explained as follows:

If the frequency dependency of loads is neglected, the total overload can be calculated using (1), and consequently total load to be shed can be calculated using (2) [12].

$$pu\ Overload = \frac{Load - Remaining\ Generation}{Remaining\ Generation} \tag{1}$$

$$pu\ Total\ Load\ to\ be\ Shed = \frac{pu\ Overload}{1 + pu\ Overload} \tag{2}$$

It implies that 50% loss of generation creates a 100% overloading on the remaining generators. Thus, at a 100% overload, only 50% of the total load in the system needs to be shed to match the load and generation and this has neglected the frequency dependency of the loads. Therefore, in the present scheme, load shedding would be more than the required amount giving rise to over frequency tripping of remaining generators as well.

Present load shedding scheme has five shedding stages and a step initiated by rate of change of frequency (df/dt). In the fifth step also there is a component embedded, which is initiated by df/dt. Even though it is not set as a rule, it is recommended to have 3 to 5 load shedding stages in a static load shedding scheme [13].

Frequency settings and time settings of the present scheme indicate delayed scenario for shedding the loads. On the other hand, breakers have their own operation time depending on their construction. It is recommended that if the current load shedding scheme to be continued the operation times of the breakers has to be investigated and the time settings of the under frequency relays must be evaluated and corrected accordingly. Otherwise, the scheme would not respond in the manner it is designed for.

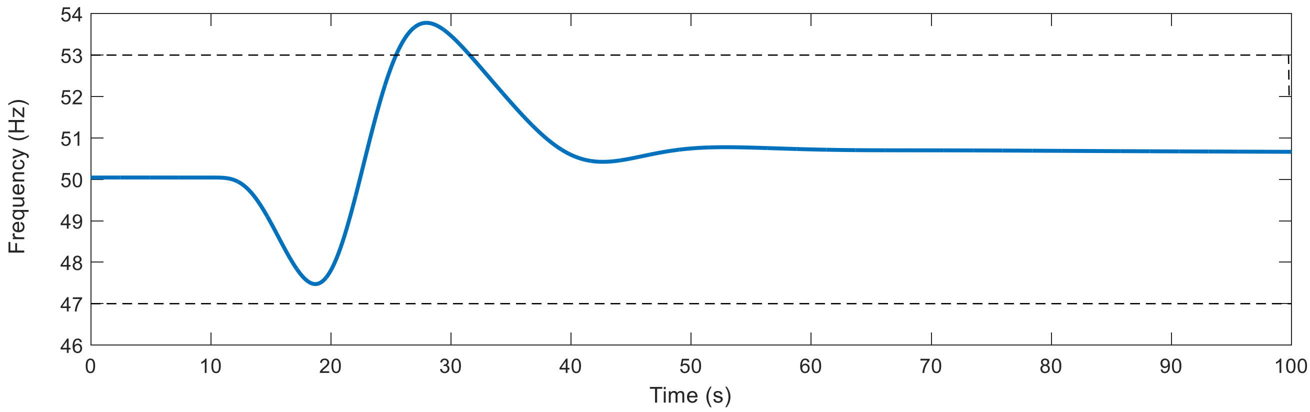

Fig. 12 System frequency response at the loss of 255 MW loaded Puttalam coal power plant.

Fig. 12 presents a good example for the above discussion. System frequency response at the loss of one of the units of the Puttalam coal power plant loaded at 255 MW is shown in Fig12.

In general, synchronous generators' under frequency and over frequency settings are at 47 Hz and 53 Hz respectively with a 3 s time delay. In this case the tripped generator was delivering 255 MW, which is 24% of the total system demand, 1052.5 MW at the time it was removed from the system. With the tripping of the generator frequency starts to decay and load shedding happens as implemented in the present load shedding scheme of CEB. In this case all five stages of the scheme get initiated, thus tripping 36% (379 MW) of the total load, 1052.5 MW. Since the load shedding is more than 12% higher than the generation loss, system frequency swings back rapidly, which goes above the over frequency limits (53 Hz for 3 s) of most of the generators, which would trip off the remaining generators from the system leading to a blackout (generator protection relays are not implemented in this case and therefore, the above explained cascaded failure is not represented in Fig. 12).

This case study gives a clear indication that with the present load shedding scheme, single unit of a Puttalam coal power plant cannot be loaded even to 25% of the total system demand. Therefore, if it is required to harness the maximum possible capacity of a single generator unit, present load shedding scheme needs to be revised.

5.2.2 Proposing Load Shedding Scheme

Section 5.2.1 discussed the weaknesses of the present load shedding scheme. The major drawback identified is the shedding of unnecessarily a larger percentage of the total load than what is required to gain the power balance after a contingency. In the light of the above observations, the following load shedding scheme is proposed.

Table I: Proposing Under Frequency load Shedding Scheme

Stage	Load Shedding Criteria	Load per Stage
I	49 Hz + 100 ms	6%
II	48.75 Hz + 100 ms	6%
III	48.50 Hz	9%
IV	48.25 Hz	9%
df/dt	49.5 Hz AND df/dt < -0.6 Hz/s	13.5%
Total	df/dt	13.5%
	Frequency only	30%

Decision of the total load to shed

As previously discussed, at a 100% overload, 50% of the total load in the system has to be shed to balance generation and demand if frequency dependency of loads is neglected. In considering the frequency dependency, load damping coefficient, ***d*** can be defined as given in (3), and thus, total load to be shed can be calculated using (4), [14] - [15].

$$d = \frac{\Delta P/P}{\Delta f/f} \tag{3}$$

Where

P – Rated Power; ***ΔP*** – Power deviation;

f – System frequency and ***Δf*** – frequency deviation.

$$P_{shed} = \frac{\frac{\Delta P_{max\ overload}}{1+\Delta P_{max\ overload}} - d(\frac{\Delta f}{f})}{1-d(\frac{\Delta f}{f})} \tag{4}$$

Where,

P_{shed} – Maximum per unit overload;

$\Delta P_{max\ overload}$ – Maximum per unit overload;

f – System frequency;

Δf – maximum allowed frequency deviation ($f - f_{min}$);

d– load damping coefficient.

In general, the load damping coefficient is in the range of 0 – 7 [14]. Thus, for a 100% maximum overload, if minimum frequency setting is selected as 48.25 Hz and load damping coefficient is selected as 2.5, the total load to be shed would be 45%.

In the designed system after several system studies 43.5% of total load is selected to be shed. In [16], survey results of practically implemented load shedding schemes around the world are analyzed. According to the results given in [16], the total load shed in many countries (power grids) lies in the range of 30% to 50%.

Decision of the number of load shedding stages and the size of load to shed at each stage

The number of load shedding steps and the size of each step are influenced by the factors such as system inertia constant, percentage overload and reactive support by generation during system disturbances. Generally four load shedding steps are recommended considering the economics aspects and complexity. It is also recommended that the value of the load to be shed at various stages to be increased with every stage [17]. According to [16], the number of load shedding stages and average percentage load shed at each stage is not consistent around the world. However, majority of the cases in [16] have adopted three to five load shedding stages.

Considering the above facts, available feeder loads, following the CEB priority criteria in feeder selection at each stage, and considering the initial system studies, 6%, 6%, 9% and 9% of the total load were selected to shed in the four stages respectively. Considering the Puttalam power plant having three units totaling 900 MW, and embedded generation in the system, additional emergency step initiated by rate of change of frequency (df/dt) is included to the proposing load shedding scheme. A 13.5% of the total load is shed in this df/dt initiated step making the total load shed to be 43.5%.

Decision of the rate of change of frequency thresholds and frequency

The frequency at which the load shedding program starts was decided by considering the lowest frequency at which generators are allowed to run for long periods. That is, the first step frequency is usually set below the system normal operating or the frequency at which the system could continue to operate. Nominal frequency of the Sri Lanka Power System is 50 Hz and the allowable limits for variations are within ±1% as given in the Grid Planning and Operating Standards [18]. Therefore, for the emergency step initiated by both frequency and rate of change of frequency, 49.5 Hz frequency setting is selected. For the load shedding stage 1, 49 Hz is selected allowing a margin for temporary abnormal situations in the system, which avoids spurious tripping of loads.

The frequency setting of the final load shedding stage should be above the under frequency protection setting of the critical generator in the system. In general, for most of the power plants in Sri Lanka, the under frequency relay setting is at 47 Hz with 3 s time delay. Considering the aforementioned critical minimum frequency setting as well as the fact of having limited spinning reserve in the system, the minimum frequency of the load shedding scheme was selected as 48.25 Hz to avoid any critical condition. The other two intermediate frequency settings were selected as 48.75 Hz and 48.5 Hz keeping equal frequency steps between stages.

In selecting the rate of change of frequency setting to initiate the emergency step, swing equation given in (5) is considered. The critical power imbalance is decided based on the system spinning reserve and initial transient studies on the system. The standard spinning reserve of the Sri Lanka power system is 5%. Having three units in the Puttalam power station, the system equivalent inertia constant is around 5 s [19]. Considering the above facts and the frequency dependency of loads, 20% generation loss is considered as a critical scenario.

$$\frac{df}{dt} = \frac{f_0}{2H}(\Delta P - d\Delta f) \tag{5}$$

Where,

$\Delta P_{overload}$ – per unit overload;

$d\Delta f$ – per unit load reduction due to frequency dependency;

H – system inertia constant;

f – system frequency;

f_o – rated frequency

Therefore, at 20% generation loss, considering load damping coefficient of 2.5, equivalent inertia constant of 5 s and minimum frequency of 48.25 Hz; the rate of change of frequency becomes -0.56 Hz/s. Therefore, rate of change of frequency setting for emergency step is taken as -0.6 Hz/s.

Setting the time delays

A time delay is necessary to prevent unnecessary shedding of load during the frequency oscillations, which can occur on the load bus. However, it is advantageous to keep the time delay setting of the frequency relays as short as possible. This avoids an unnecessarily large decay of frequency, avoiding spurious tripping of loads. Time delays of the relays in the first two stages were set at 5 cycles and the relays of stages 3 and 4 are set to trip instantaneously if frequency criteria are satisfied. Further, all the load breakers were simulated with an operating time delay of 4 cycles.

5.3 Transient Stability of the System under Different Contingencies

The main objective of this research is to find the optimal size of the single largest generator based on system transient stability criteria. Therefore, the system transient stability was analyzed under different system contingencies in the off-peak period using the developed power system simulation model of Sri Lanka. The performance of the existing load shedding scheme was compared against the proposing load shedding scheme evaluating the ability of the power system to operate within the CEB standards and protection limits avoiding cascaded failure.

5.3.1 Case 1: Tripping 160 MW loaded Puttalam unit (Loosing 15% generation – single unit trip)

In this case all three units of the Puttalam power plant were loaded at 160 MW each and the swing bus victoria power station was giving 46 MW. Total system demand was not changed and it was at 1052.5 MW and 432.2 kvar. Therefore, the largest generator loading in this case is 15% of the total demand. One of the units of Puttalam power plant was tripped at the simulation time, t = 20 s and the system frequency response measured at the Biyagama Bus is shown in Fig. 13 for both cases: when present load shedding scheme was used and when proposed load shedding scheme was used.

Fig. 13 indicates that when the highest generator loading is 15% and if it is tripped off, the system is still transiently stable with both present CEB load shedding scheme and new proposing load shedding scheme. In the case of CEB load shedding only the first stage of loads (7.5% of the total load) is shed and the remaining power imbalance is taken care of with the system inertia and spinning reserve. In the case of new load shedding scheme both first and second stages of loads totaling 12% of the total load is shed, which is the reason for the observable comparatively higher frequency swing back. However, with both load shedding schemes frequency is maintained well within the CEB standards and generator protection limits during and after the disturbance.

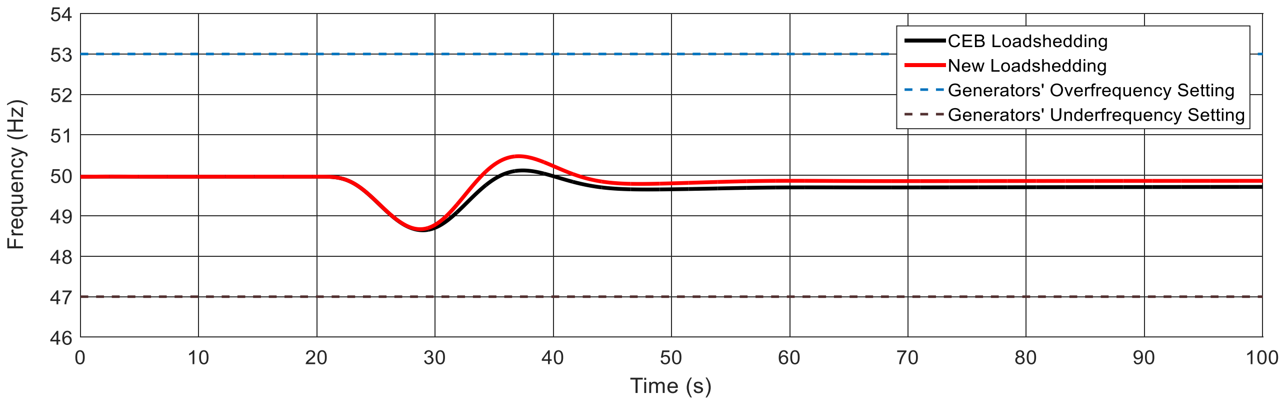

Fig. 13 System frequency response at the loss of 160 MW (15% of total demand) loaded Puttalam coal power unit.

5.3.2 Case 2: Tripping 160 MW loaded two Puttalam units simultaneously (Losing 30% generation – two units trip)

In this case all three units of the Puttalam power plant were loaded at 160 MW each and the swing bus victoria power station was giving 46 MW. Total system demand was not changed and it was at 1052.5 MW and 432.2 kvar. Therefore, the largest generator loading in this case is 15% of the total demand. However, simultaneous tripping of two units at the Puttalam power plant was simulated in this case. Therefore, 30% of the generation was tripped at t = 20 s and the system frequency response measured at the Biyagama Bus is shown in Fig. 14 for both cases: when present load shedding scheme was used and when proposed load shedding scheme was used.

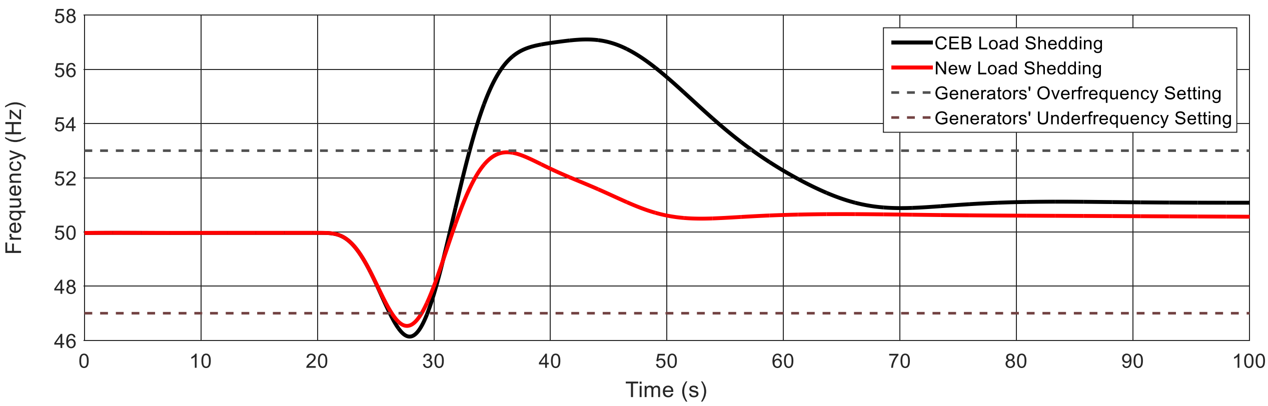

Fig. 14 System frequency response at the loss of 320 MW (30% of total demand) at the Puttalam coal power plant.

Fig. 14 indicates that when the highest generator loading is 15% and if two of such loaded units at the Puttalam power plant were tripped off (totaling 30% generation loss) the system is not transiently stable with the present CEB load shedding scheme. In this case all the stages of loads including the df/dt initiated step were shed totaling 60.5% of load shed. Frequency response in Fig. 14 shows that it violates both under and over-frequency protection limits for generators. Therefore, if protective relays were modeled in this case, system total failure could have observed.

However, with the new proposing load shedding scheme system is transiently stable. With the new also all stages of loads including the df/dt step, totaling 43.5% of the total load is shed. However, Fig. 14 shows that frequency is maintained marginally within the CEB standards and generator protection limits during and after the disturbance. If the new load shedding scheme is implemented such loss of 30% generation would be able to tolerated marginally, without going to a total system failure. Nevertheless, if embedded generators also get tripped off due to system transients, it is possible to trip more generation due to under-frequency protection of generators leading to a blackout.

5.3.3 Case 3: Tripping 206 MW loaded Puttalam unit (Loosing 20% generation – single unit trip)

In this case, all three units of the Puttalam power plant were loaded at 206 MW each and the swing bus victoria power station was giving 45 MW. Total system demand was not changed and it was at 1052.5 MW and 432.2 kvar and therefore, in order to match the load and generation, Kothmale power plant was not dispatched in this case. The largest generator loading in this case is 20% of the total demand. One of the units of Puttalam power plant was tripped at the simulation time, t = 20 s and the system frequency response measured at the Biyagama Bus is shown in Fig. 15 for both cases: when present load shedding scheme was used and when proposed load shedding scheme was used. With CEB load shedding three stages of loads shed totaling 26% while with the new scheme four stages of loads shed totaling 30%. Frequency responses are almost similar for both cases and the system is operating well within the standards and protection settings.

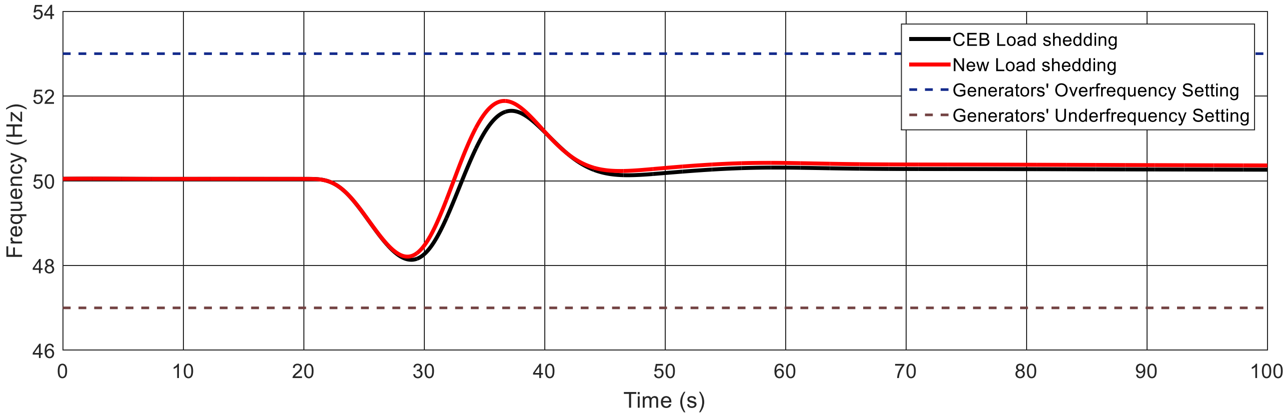

Fig. 15 System frequency response at the loss of 206 MW (20% of total demand) loaded Puttalam coal power unit.

5.3.4 Case 4: Tripping 255 MW loaded Puttalam unit (Losing 24% generation – single unit trip)

In this case, two units of the Puttalam power plant were loaded at 255 MW each, other unit at 100 MW and the swing bus victoria power station was giving 46 MW. Total system demand was not changed and it was at 1052.5 MW and 432.2 kvar and therefore, in order to match the load and generation, Kothmale power plant was not dispatched in this case. The largest generator loading in this case is about 25% of the total demand. One of the 255 MW loaded unit of Puttalam power plant was tripped at the simulation time, t = 20 s and the system frequency response measured at the Biyagama Bus is shown in Fig. 16 for both cases: when present load shedding scheme was used and when proposed load shedding scheme was used. With both load shedding schemes all of the set steps get activated, where CEB scheme sheds 60.5% of the load and new scheme sheds 43.5% of the load.

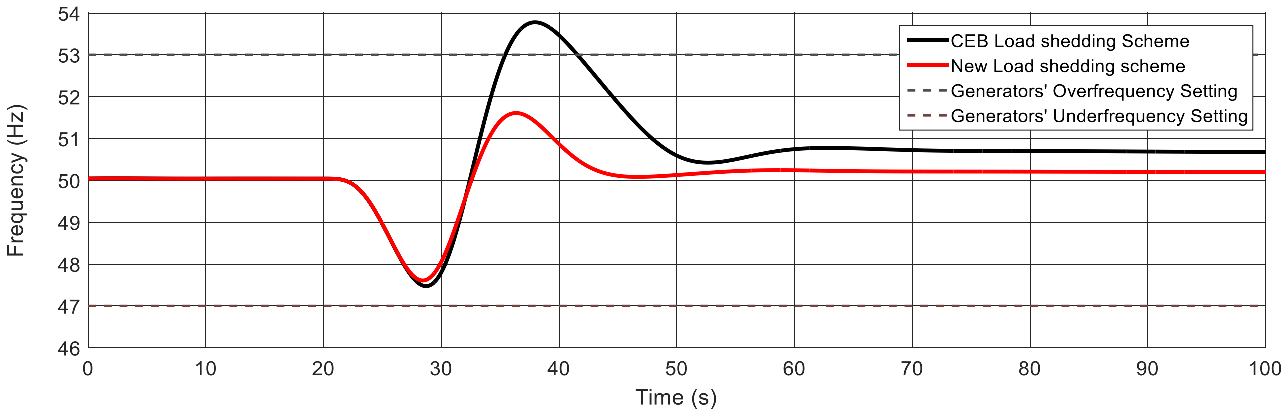

Fig. 16 System frequency response at the loss of 255 MW (25% of total demand) loaded Puttalam coal power unit.

Frequency response in Fig. 16 shows that with CEB load shedding scheme, it violates the over-frequency protection limits for generators. Therefore, if protective relays were modeled in this case, system total failure could have observed due to tripping of more generation in the system. Therefore, with the present load shedding scheme of CEB, single generator unit cannot be loaded to 25% as it can lead to a system blackout if that maximum loaded generator get tripped off.

However, with the new proposing load shedding scheme, the system is transiently stable. Fig. 16 shows that frequency is maintained well within the CEB standards and generator protection limits during and after the disturbance. Therefore, if the proposing load shedding scheme is used maximum loading of a single unit can be set at 25% of the total demand.

5.3.5 Case 4: Tripping 285 MW loaded Puttalam unit (Loosing 27% generation – single unit trip)

In this case, two units of the Puttalam power plant were loaded at 156 MW each, other unit at 285 MW and the swing bus victoria power station was giving 47 MW. Total system demand was not changed and it was at 1052.5 MW and 432.2 kvar and therefore, in order to match the load and generation, Kothmale power plant was not dispatched in this case. The largest generator loading in this case is 27% of the total demand, and this 285 MW loaded unit of Puttalam power plant was tripped at the simulation time, t = 20 s and the system frequency response measured at the Biyagama Bus is shown in Fig. 17 for both cases: when present load shedding scheme was used and when proposed load shedding scheme was used. With both load shedding schemes all of the set steps get activated, where CEB scheme sheds 60.5% of the load and new scheme sheds 43.5% of the load.

As it was observed in section 5.3.4, with the CEB load shedding scheme generators cannot be loaded to 25%. Therefore, as expected with 27% loaded generator getting tripped off, it violates the over-frequency protection limits for generators. Therefore, if protective relays were modeled in this case, system blackout could have observed due to tripping of more generation in the system.

However, with the new proposing load shedding scheme, the system is transiently stable. Fig. 17 shows that frequency is maintained well within the CEB standards and generator protection limits during and after the disturbance. Therefore, if the proposing load shedding scheme is used, a generator unit can be loaded to 27% of the maximum demand assuring system to be transiently stable at an (n-1) contingency.

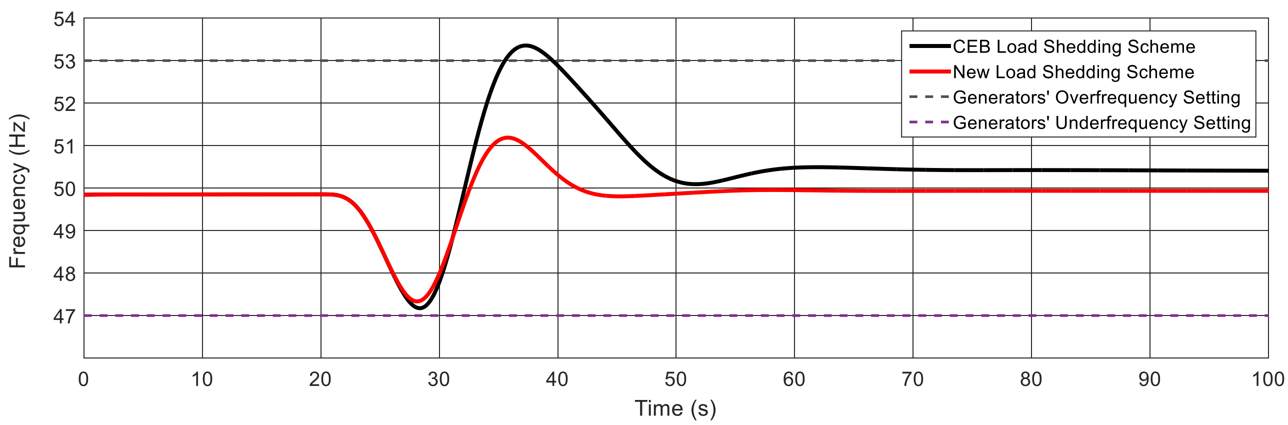

Fig. 17 System frequency response at the loss of 285 MW (27% of total demand) loaded Puttalam coal power unit.

6 Conclusions

A simulation model of the Sri Lankan power system was developed in PSCAD/EMTDC and validated using actual system data. The model was specifically developed to study the system transients during off-peak hours of load demand. The developed simulation model presents stable operation under various power system contingencies and behaves robustly at different load flow conditions. This model can be effectively used for transient stability simulation studies in the off-peak hours. Also it can be easily augmented with required loads and generation to study any operating point on the load curve of Sri Lanka.

It was shown that present load shedding scheme has several weaknesses and these weaknesses were clearly observed during the simulation studies under the tested loading conditions.

Transient stability studies under different contingencies shows that, with the present load shedding scheme of CEB maximum loading of a single generator unit has to be limited to 20% of the total system demand to maintain the transient stability under (n-1) contingency.

Authors have proposed a new, simple static load shedding scheme explaining how it was implemented in steps. If the proposed load shedding scheme is implemented, the system would be able to maintain the transient stability under (n-1) contingency, provided that the maximum loading of a single generator unit is kept less than 30% of the total system demand.

Therefore, optimal size of the single largest generator based on system transient stability criteria is 20% of the total demand with the present load shedding scheme of CEB. However, it can be increased to 30%, if the proposed load shedding scheme is implemented.

7 Recommendations

The results of this research lead to the following recommendations:

1. Present load shedding scheme of CEB has several weaknesses and load shedding scheme has to be revised.
2. If present load shedding scheme is continued to be used:
    - Operating times of the feeder breakers has to be investigated and time settings of the relays has to be revised accordingly for the load shedding scheme to be operated as expected
    - In order to maintain the system transient stability under (n-1) contingencies, optimal size of the single largest generator has to be limited to 20% of the total system demand.
3. If proposed load shedding scheme is implemented:
    - Optimal size of the single largest generator can be increased to 30% of the total system demand, maintaining the system transient stability under (n-1) contingencies.
    - Proposed scheme has to be tested for peak demand period before implementing in the actual system.

8 Acknowledgments

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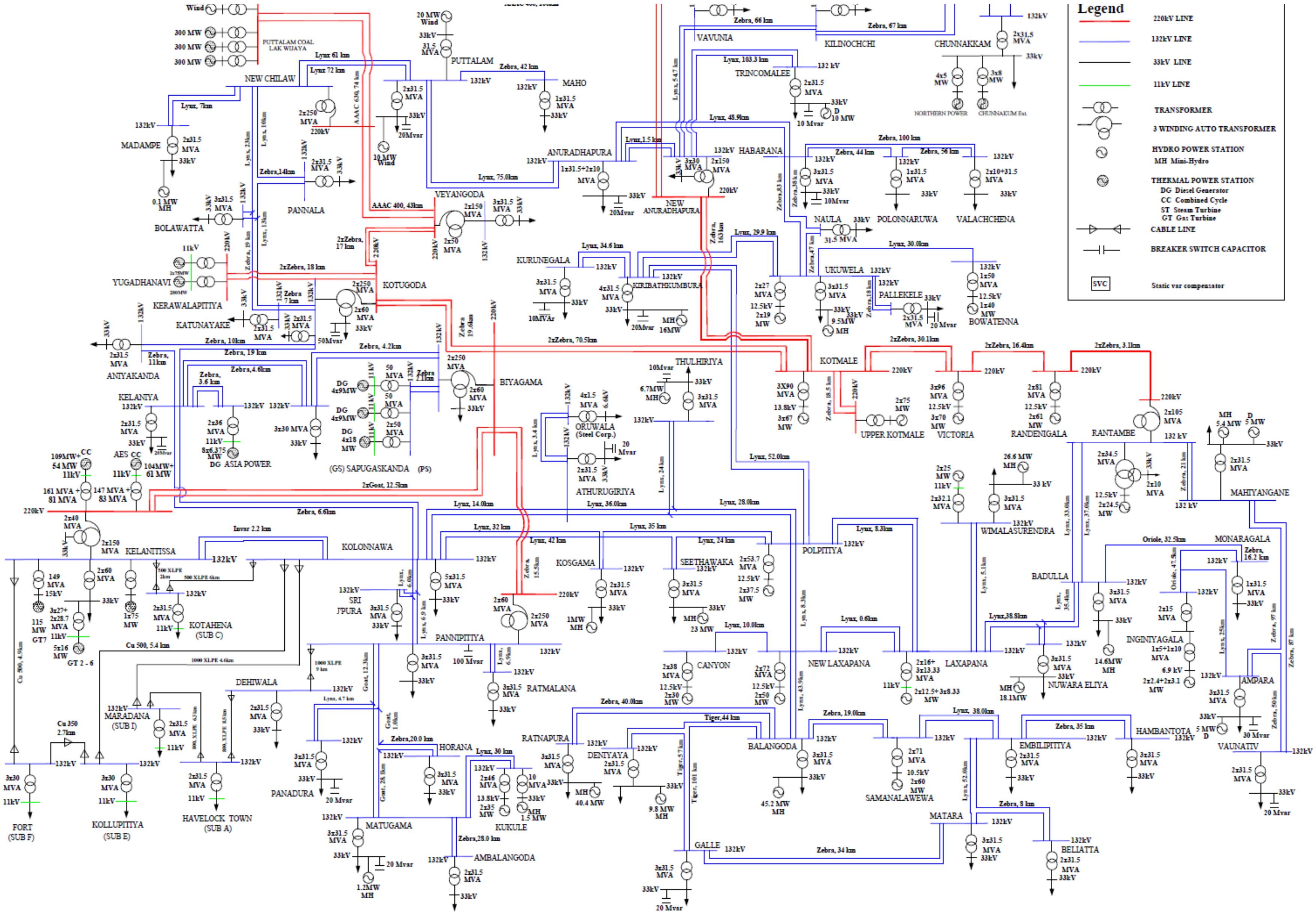
Annexure A.1 - Power System Load Distribution – Off-peak situation

Bus Name	Pload (MW)	Qload (Mvar)
WIMAL-3 33.000	12.7	2.4
AMPA-3 33.000	27.1	4.3
UKUWE-3 33.000	22.7	7.1
VAVUN-33 33.000	12.3	1.6
KELAN-3A 33.000	4.7	2.9
KELAN-3B 33.000	4.7	2.9
NAULA-3 33.000	8.5	2.2
BELIAT-3 33.000	23.8	6.1
HAMBA-33 33.000	6.3	1.8
HAMBA-33 33.000	12.4	3.5
HORANA_3 33.000	18	14.3
KATUNA-3 33.000	19.3	5.8
MAHO-3 33.000	4.4	1.6
VAUNAT-3 33.000	0	0
PALLEK-3 33.000	16.3	4.5
KOSGA-3 33.000	20.2	9.2
SITHA-33 33.000	18.2	6.3
NUWAR-3 33.000	19.4	4.9
THULH-3 33.000	28.4	13.5
ORUWA-3 33.000	0.8	0.2
KOLON-3A 33.000	18.7	11.6
KOLON-3B 33.000	17.4	10.8
PANNI-3 33.000	18.1	8.6
BIYAG-3 33.000	38.5	19.2
KOTUG-3 33.000	20.5	17.2
KOTUG-NEW 33.000	10.8	9.0
SAPUG-3A 33.000	32.9	20.7
BOLAW-3 33.000	28.1	15.5
BADUL-3 33.000	23.9	3.7
BALAN-3 33.000	11.8	2.4
DENIY-3 33.000	13.5	3.6
GALLE-3 33.000	17.2	9.6
GALLE-3B 33.000	9.0	5.0
EMBIL-3 33.000	24.1	4.8
MATARA-3 33.000	17.8	4.6
KURUN-3 33.000	22.4	4.3
HABAR-3 33.000	23.2	6.0
ANURA-3A 33.000	10.1	2.1
ANURA-3B 33.000	6.4	1.3
NEWANU-3 33.000	11.7	2.4
TRINC-3 33.000	23.1	7.8

KILINOCH_3 33.000	5.9	0.8
CHUNNAKAM-3 33.000	25.7	5.2
RATNAP-3 33.000	11.2	4.8
KIRIB-3 33.000	23.7	6.6
VALACH_3 33.000	4.0	2.0
VALACH-3B 33.000	6.2	3.2
RATMA-3A 33.000	23	10.5
MATUG-3 33.000	21.2	12.6
PUTTA-3 33.000	16.3	5.9
CEMENT 33.000	0	0
ATURU-3 33.000	14.1	5.4
VEYAN-33 33.000	18.3	13.2
JPURA_3 33.000	20	9.1
PANAD-3 33.000	21.6	9.4
MADAM-3 33.000	17.4	8.8
K-NIYA-3 33.000	9.8	4.8
AMBALA 33.000	14.3	3.7
DEHIW_3 33.000	14.8	8
PANNAL 33.000	19.6	9.9
ANIYA 33.000	19.5	9.2
MAHIYA-3 33.000	6.7	2.9
COL_I_11 11.000	7.9	3.5
COL_A_11 11.000	13.8	5.5
COL_E-11 11.000	13.8	6.9
COL_F-11 11.000	17.0	10.6
COL_C-11 11.000	7.3	4.5
Total	**1052.5**	**432.3**

Annexure A.2 – Schematic Diagram of the 2015 Transmission System



Annexure A.3 - Installed Generation Capacities in Sri Lanka Power System

Name of the Generating Plant	Location	Generation Units	Capacity (MW)	Commercial Operation Date
New Laxapana	Laxapana	1	57.6	Feb/ Mar 1974 (Rehabilitated in 2014)
		2	57.6	Feb/ Mar 1974 (Rehabilitated in 2014)
Old Laxapana	Laxapana	1	9.5	Dec-50 (Rehabilitated in 2014)
		2	9.5	Dec-50 (Rehabilitated in 2014)
		3	9.5	Dec-50 (Rehabilitated in 2014)
		4	12.5	Dec-58
		5	12.5	Dec-58
Wimalasurendra	Norton Bridge	1	25	Jan-65 (Rehabilitated in 2014)
		2	25	Jan-65 (Rehabilitated in 2014)
Polpitiya (Samanala)	Pitawala	1	37.5	Apr-69
		2	37.5	Apr-69
Canyon	Maskeliya	1	30	Mar-83
		2	30	May-88
	sub total	353.70 MW		
Name of the Generating Plant	**Location**	**Generation Units**	**Capacity (MW)**	**Commercial Operation Date**
Kothmale	Mawathura Gampola	1	67	Apr-85
		2	67	Feb-88
		3	67	Feb-89
Victoria	Hakurutale Adhikarigama	1	70	Jan-85
		2	70	Oct-84
		3	70	Feb-86
Ukuwela	Matale	1	20	July / August 1976 (Rehabilitated in 2011)
		2	20	July / August 1976 (Rehabilitated in 2011)
Bowatenna	Naula	1	40	Jun-81
Randenigala	Randenigala	1	61	Jul-86
		2	61	Jul-86
Rantambe	Rantambe	1	25	Jan-90
		2	25	Jan-90
Nilambe	Nilambe, Doluwa	1	3	Jul-88
Upper Kothmale	Niyamgamdora, Kothmale	1	75	Mar-12
		2	75	Jun-12
	sub total	816.00 MW		

Name of the Generating Plant	Location	Generation Units	Capacity (MW)	Commercial Operation Date
Samanala wewa	Kapugala Balangoda	1	60	Oct-92
		2	60	Oct-92
Kukule	Molkawa	1	37	Jul-03
		2	37	Jul-03
Udawalawe	Udawalawe	1	6	Apr-69
Inginiyagala	Inginiyagala	1	11	Jun-63
Wind	Hambantota	1	3	1999
	sub total	214.00 MW		
Name of the Generating Plant	**Location**	**Generation Units**	**Capacity (MW)**	**Commercial Operation Date**
KPS Gas Turbine	Wellampitiya	1	20	Nov-80
		2	20	Mar-81
		3	20	Apr-81
		4	20	Dec-81
		5	20	Apr-82
KPS Gas Turbine 7	Wellampitiya	1	115	Aug-97
KCCP (GT8 + ST)	Wellampitiya	1	165	Aug-02
Sapugaskanda Diesel A	Heiyanthuduwa	1	20	May-84
		2	20	May-84
		3	20	Sep-84
		4	20	Oct-84
Sapugaskanda Diesl B	Heiyanthuduwa	1	10	Sep-97
		2	10	Sep-97
		3	10	Sep-97
		4	10	Sep-97
		5	10	Oct-99
		6	10	Oct-99
		7	10	Oct-99
		8	10	Oct-99
Puttalam Lakvijaya Coal Plant	Narakkalliya, Norochcholai, Puttalam	1	300	Jul-11
		2	300	May-14
		3	300	Oct-14
Uthuru Janani	Chunnakam	1	8.9	Jan-13
		2	8.9	Jan-13
		3	8.9	Jan-13
	sub total	1467.70 MW		