Performance Measurements of Generation and Transmission Systems

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Content

1. Introduction

System and network performance standards are important issues in modern power system as they ensure the efficient and secure functioning of the power system and appropriate quality of electricity supply. Therefore there is a demand for common indicators that enable system operators and others to evaluate their performance. These indicators measure the reliability of electric power service and reflect operational problems. Moreover, they can also be used as a tool to compare or benchmark the power system performance among utilities and generation plants.

This document is intended to identify the key performance indicators and their definitions which are currently used worldwide to assess the technical and financial performance of generation and transmission systems.

2. Transmission Performance Indicators

Electricity transmission companies normally measure their performance by using various types of qualitative and quantitative assessments. They measure achievements of their objectives through monitoring number of performance indicators. Performance Indicators are the parameters that are related to transmission lines or transformers availability, service continuity or voltage wave. The indicators for the present technical performance of the transmission system are useful when planning the future developments to ensure a high degree of reliability of the transmission system.

2.1 Transmission System Availability Indicators

Availability of a Transmission System is expressed as a function of the Transmission Circuit Outages or Interruptions and it is evaluated using indicators that measure the number of outages and their durations. Availability Indices could be measured in terms of the scheduled (planned) and forced outages separately or in term of overall outages. These interruptions also could be classified as transient interruptions, long interruptions (Eg: More than 3 mins) and short interruption (Eg: Less than 3 mins) according to their duration. Also the Transmission Line availability indices could be measured categorized in terms of transmission voltage.

Transmission System availability of a Transmission system can be assessed through Individual Performance Indicators and Overall Performance Indicators. Individual Performance Indicators are used to measure Transmission System availability of each individual Transmission Line and each individual Grid Substation Transformer.
The Individual Performance Indices are defined below.

- **Transmission Line Interruption Duration per Year (in Hours)**

  This measures the average time duration per year where a single transmission line is not available in service.

$$UD_L = \frac{\sum_{j=1}^{NL} \sum_{i=1}^{kt} H_{i,j}}{NL}$$

Where;
UD_L = Annual Unavailable Duration (in hours) of a Transmission Line
$H_{i,j}$ = Duration of Outage "i", that affected Transmission Line "j" (in hours)
NL = Total number of Transmission Lines
kt = Total number of Outages of Transmission Line "j" during the reported year

- **Substation Transformer Interruption Duration per Year (in Hours)**

  This measures the average time duration per year where a single substation transformer is not available in service.

$$UD_T = \frac{\sum_{j=1}^{NT} \sum_{i=1}^{kt} H_{i,j}}{NT}$$

Where;
UD_T = Annual Unavailable Duration (in hours) of a Substation Transformer
$H_{i,j}$ = Duration of Outage "i", that affected Substation Transformer "j" (in hours)
NT = Total number of Substation Transformers
kt = Total number of Outages of Substation Transformer "j" during the reported year

- **System Average Frequency of Outages of Transmission Line per Year**

  This measures the number of interruptions per year per transmission line of the system.

$$SAFO_L = \frac{\sum_{j=1}^{NL} NO_j}{NL}$$

Where;

$SAFO_L$ = System Average Frequency of Outages of Transmission Line per Year

NO_j = Number of Outages of Transmission Line "j" during the reported year

NL = Total number of Transmission Lines

Transmission Line outages also can be classified according to the duration of the outages (Eg: Ranging from less than ten minutes to greater than 4 weeks) and total number of outages in each time classification could be measured.

- **System Average Frequency of Outages of Substation Transformer per Year**

  This measures the number of interruptions per year per substation transformer of the system.

$$SAFO_T = \frac{\sum_{j=1}^{NL} NO_j}{NT}$$

Where;

$SAFO_T$ = System Average Frequency of Outages of Substation Transformer per Year

NO_j = Number of Outages of Transmission Transformer "j" during the reported year

NL = Total number of Transmission Transformers

Transformer outages also can be classified according to the duration of the outages (Eg: Ranging from less than ten minutes to greater than 4 weeks) and total number of outages in each time classification could be measured.

Overall System Performance Indices which are used to measure overall Transmission System availability are defined below.

- **Overall System Unavailability – Transmission Lines**

  This measures the average fraction of time (expressed in percent) that Transmission Lines are unavailable and disconnected from the Transmission System.

$$SU_L = \frac{\sum_{j=1}^{NL} \sum_{i=1}^{kt} H_{i,j}}{NL * 8760} \text{ x } 100$$

Where;

SU_L = System Unavailability (Transmission Lines)

$H_{i,j}$ = Duration of Outage "i", that affected Transmission Line "j" (in hours).

NL = Total number of Transmission Lines

kt = Total number of Outages of Transmission Line "j" during the reported year

- **Transmission Line Availability**

SA_L = (100 - SU_L) %

Where;
SA_L = Transmission Line Availability
SU_L = System Unavailability (Transmission Lines)

- **System Transmission Transformer Unavailability**

This can be measured taking the fraction of time (expressed in percent) that Transmission Transformers are unavailable and disconnected from the Transmission System or by considering the extent of which the power transformer capacity remained unavailable.

$$SU_T = \frac{\sum_{j=1}^{NT}\sum_{i=1}^{kt} H_{i,j}}{NT*8760} \text{ x } 100 \quad \text{or} \quad SU_T = \frac{\sum_{j=1}^{NT}\sum_{i=1}^{kt} H_{i,j}*C_j}{TC*8760} \text{ x } 100$$

Where;
SU_T = System Unavailability (Substation Transformer)
$H_{i,j}$ = Duration of Outage "i", that affected Transmission Transformer "j" (in hours)
C_j = Capacity of Transmission Transformer "j" (in MVA)
NT = Total number of Transmission Transformers
kt = Total number of Outages of Transmission Transformer "j" during the reported year
TC = Total Installed Capacity of Substation Transformers (in MVA)

- **Transmission Transformer Availability**

SA_T = (100 – SU_T) %

Where;
SA_T = Transmission Transformer Availability
SU_L = System Unavailability (Substation Transformer)

- **System Average Frequency of Outages per km**

This measures the average number of Outages per km of Transmission Lines (Expressed in number of outages per 100 km of lines)

$$SAFO\_L_{100} = \frac{\sum_{j=1}^{NL} NO_j}{\sum_{j=1}^{NL} LONG_j \Big/ 100}$$

Where;

$SAFO\_L_{100}$ = System Average Frequency of Outages per 100km

NO_j = Number of Outages of Transmission Line "j" during the reported year

NL = Total number of Transmission Lines

$LONG_j$ = Length of Transmission Line "j"

2.2 Transmission System Power Quality Indicators

To assess the performance of a transmission system not only the availability but also the quality of the power must be considered. Power quality indicators shows how the transmission line parameters comply with the defined standards.

The power quality measures and indicators are defined below.

- **Frequency Excursions**

  Frequency variation is the deviation of frequency beyond a certain range from the nominal supply frequency. Any frequency excursions outside these limits for a defined duration or more (Eg: 60 Seconds) could be recorded as frequency limit violations.

  In Sri Lanka the nominal fundamental frequency range shall be 50 Hz ± 1%. Frequency deviation indices can be defined to find the number of time or duration that the system frequency goes beyond the allowable range.

  To figure out the extent of frequency excursions, frequency ranges can be also defined;

  (If the nominal frequency is *f)*

  1. *Normal State*
     The Transmission System frequency is within the limit of (*f ± 1%)*

  2. *Alert State*
     The Transmission System frequency is beyond the normal operating limit but within (*f ± 2%)*

  3. *Emergency State*
     There is generation deficiency and frequency is below (*f - 2%)*

- **Voltage Excursions**

Voltage variation is the deviation of voltage in a certain range. Voltage deviations can be identified by monitoring the bus bar voltages of the grid substations.

According to the defined Sri Lankan Transmission System Standards, bus bar voltage magnitudes must comply with following allowed range of variation.

Voltage	Normal Condition	Single Contingency
220kV	± 5%	-10% to +5%
132kV	± 10%	± 10%

Voltage deviation indices can be defined to find the frequency or duration that the bus bar voltages violate the allowed voltage range.

- Number of voltage excursions exceeded *n* minutes per year
- Percentage of time that the transmission voltage exceeds the permissible limits

- **Voltage Unbalance**

The phase voltages of a 3-phase supply should be equal in magnitude and phase angle. The unbalance in phase voltages could be computed as follows;

$$\%\ \text{Voltage Unbalance} = \frac{\text{Max Deviation from Mean of } \{V_{RY}, V_{YB}, V_{BR}\}}{\text{Mean of } \{V_{RY}, V_{YB}, V_{BR}\}} \times 100$$

Where,
V_{RY} = Voltage between R & Y phases

V_{YB} = Voltage between Y & B phases

V_{BR}= Voltage between B & R phases

Voltage imbalance indices can be defined as a limit of imbalance level (Eg: 220kV – 2%)

- **Flicker**

Voltage Flicker is a rapid change in voltage that is typically caused by user equipment that distorts or interferes with the normal sinusoidal voltage waveform of the Transmission Network. Flicker is the visual phenomenon which causes changes in the luminance of lamps and could be annoying to people above a certain threshold.

In general the limits of the total Voltage Flicker at a Point of Common Coupling can be defined;

(a) ± 1% of the steady state voltage level, when these occur repetitively

(b) ± 3% of the steady state voltage level, when these occur infrequently

To assess the flicker occurrence, the indices can be defined to find the number of time or duration that the flicker level goes beyond the allowable range.

- **Harmonic distortion**

Harmonic Distortions are integer multiples of the fundamental power system frequency. Harmonics of the supply voltage are caused mainly by the non-linear devices connected to the system.

In general, the maximum total levels of harmonic distortion on the System under any operation condition can be defined to not exceed the values;

- 220kV - a Total Harmonic Distortion of 2% with no individual harmonic greater than 1.5%
- 132kV - a Total Harmonic Distortion of 2% with no individual harmonic greater of 1.5%

To assess the harmonic distortions, the indices can be defined to find the number of time or duration that the harmonic level goes beyond the allowable range.

- **Transmission Losses**

Transmission losses can be calculated as the difference between the total electrical energy received from the generating plants and the total energy supplied to all bulk supply licensees. It is usual to express losses as a percentage value rather than absolute value. The losses are measured over a definite period, normally per year.

The definition of the transmission losses is defined as;

$$\%Transmission\ Losses = \frac{\sum E_G - \sum E_T}{\sum E_G} \text{X } 100\%$$

Where;

E_G = Total Energy Generated (MWh) during reported year

E_T = Total Energy Sold to BSOB (MWh) during reported year

2.3 Supply Security Indicators

Power System security is the ability of the system to withstand sudden disturbances. To secure the supply the Transmission system must be able to deliver the power even under abnormal or faulty conditions.

- **Energy Not Supplied (ENS)**

This gives an estimation of the Energy not supplied to the connected Load due to the Interruptions of transmission circuits over a year.

$$ENS = \sum_{i=1}^{kt} PD_i * H_i$$

Where;

PD_i = Power disconnected by transmission circuit Interruption "i" (in MW).

H_i = Duration of Interruption "i" (in hours)

kt = Total number of Interruptions during the reported year

- **Overall Reliability of System**

The Overall Reliability of Supply for a transmission system is calculated using the formula;

$$1 - \left(\frac{ENS}{Total\ energy\ that\ would\ have\ been\ supplied\ by\ the\ transmission\ system}\right) \text{X } 100$$

Where;

ENS = Estimated Unsupplied Energy due to unavailability of transmission circuits

- **System Minutes Lost**

This index measures the severity of each system disturbance relative to the size of the system, in terms of duration of total system wide blackout. It is determined by calculating the ratio of unsupplied energy during an outage to the energy that would be supplied during one minute, if the supplied energy was at its peak value. One system minute indicates an equivalent of total system interruption, with the magnitude of annual system peak, for one minute

The formula used for calculating the system minutes lost is;

$$System\ Minutes = \frac{Sum\ of\ Unsupplied\ Energy\ (MWmin)}{System\ Peak\ Load\ (MW)}$$

When this index for a specific incident is greater than one minute, that incident can be normally classified as a major interruption.

2.4 Transmission System Assets Utilization

Assets which directly involve in Transmission Supply system are very critical for the secure operation are Transmission Lines and Grid Substation Transformers. Therefore they must be utilized productively by keeping records of their loading capacities.

- **Grid Substation Overloading**

Overloading of grid substations is defined based on the loading levels of grid substation power transformers. Overloading of transformers must be avoided to avoid overheating, leading to equipment damages and reducing the life time.

To assess the transformer overloadings, the indices can be defined to find the number of time or duration that the Grid Substations have overloaded over the reported year.

- **Transmission Transformer Utilization Factor**

This measures the extent utilization of the transmission transformers with respect to their rated capacities. It is the ratio of the maximum load on a transformer to its rated capacity.

$$UF_{Pk} = \frac{\sum_{j=1}^{NT} P_j}{\sum_{j=1}^{NT} C_j} \text{X } 100\%$$

Where;
UF_{Pk} = Transmission Transformer Utiliztion Factor
P_j = Recorded Peak Load of Transformer “j” (in MVA) during reported period
NT = Total number of Substation Transformers
C_j = Rated capacity of Transformer “j” (in MVA)

- **Load Factor**

Load Factor is an indicator of how steady an electrical load is over time. It is simply the average load divided by the peak load in a system over a period of time. But normally load factor is calculated subjected to the produced energy according to the following formula.

$$Load\ Factor = \frac{Total\ Generation\ During\ the\ Nominal\ Period}{Maximum\ Demand \text{ x No. of hours in the report period}}$$

Load factor of any system must be tried to keep in its maximum by pulling down the concentrated maximum demand and shifting the loads to periods of otherwise low usage. Load factor maximization is essential in maintaining the security of supply of the countries in which meeting the concentrated maximum demand is critical. Countries which have a flat load curve own a higher load factor.

2.5 Maintenance Cost Indicators

The Maintenance Cost incurred to operate a bulk supply operation business is also an indicator of the financial performance of that operation. Maintenance cost includes the costs incurred that are directly related to the well-being, security, integrity, reliability and availability of equipment and installations. Technical labor/manpower costs, material cost, spares and vehicle costs associated with normal or day today operation and maintenance activities as well as preventive and corrective maintenance activities are also included.

- **Transmission Lines Maintenance Cost Index (TLMCI)**

  This indicates the annual maintenance cost per unit length of transmission lines.

$$TLMCI = \frac{Total\ Line\ Maintenance\ Cost}{\sum_{j=1}^{NL} LONG_j}$$

Where;

TLMCI = Transmission Lines Maintenance Cost Index

NL = Total number of Transmission Lines

$LONG_j$ = Length of Transmission Line "j" in km

- **Substation Maintenance Cost Index (SMCI)**

  This indicates the annual maintenance cost per Substation.

$$SMCI = \frac{Total\ GSS\ Maintenance\ Cost}{NS}$$

Where;

SMCI = Substation Maintenance Cost Index

NS = Total number of Grid Substations

3. Generation Performance Indicators

Generation Performance Indicators are the parameters that are related to the availability, service continuity or environmental impact of a generation plant or unit. Development of common performance indicators is the first step in a process of creating large databases which would enable power plant operators to compare their own plant performances with others, and make improvements.

3.1 Plant Factor

The plant factor of a power plant is the ratio of the actual energy output of the power plant over a period of time to its potential output if it had operated at full nameplate capacity the entire time.

Plant Factors vary greatly depending on the type of power plants and it is calculated according to the following formula.

$$Plant\ Factor = \frac{Actual\ Energy\ Production\ During\ the\ Nominal\ Period}{Potential\ Energy\ Production\ During\ the\ Period}$$

3.2 Running Plant Factor

The running plant factor of a generation unit is the ratio of the actual energy output of a generation unit over a period of time to its potential output if it had operated at full nameplate capacity during the period in which it has been operated.

Running Plant Factor shows the extent to which the generation units have been operated when they are running out of their nominal capacities.

$$Running\ Plant\ Factor = \frac{Actual\ Energy\ Production\ During\ the\ Nominal\ Period\ (MWh)}{Rated\ Capacity\ (MW)\ \text{x}\ Operated\ Duration\ (h)}$$

3.3 Equivalent Full Load Hours

This gives the number of hours during one year, during which the generator would have to run at rated power in order to produce the energy delivered throughout a year.

Number of Equivalent Full Load Hours for a generator can be calculated using the formula given below.

$$Equivalent\ Full\ Load\ Hours = \frac{Annaul\ Energy\ Production}{Rated\ Power}$$

3.4 Generation Unit Cost

Electricity generation is the process of generating electrical power from other sources of primary energy. Electricity is by electromechanical generators, primarily driven by heat engines fueled by chemical combustion or by other methods such as the kinetic energy of flowing water or wind. Apart from that the other energy sources include solar photovoltaic and geothermal power.

However, there is a cost associated with power generation which mainly affects the electricity price. This cost varies with the energy source incorporated with power generation and also could be classified as energy cost and maintenance cost. The electricity generation cost of any power plant can be used to find the cost of generation per one unit (1kWh) of electricity.

$$Generation\ Unit\ Cost = \frac{Actual\ Energy\ Production\ During\ the\ Nominal\ Period}{Total\ Cost\ Incurred\ for\ Power\ Generation}$$

$$Energy\ Unit\ Cost = \frac{Actual\ Energy\ Production\ During\ the\ Nominal\ Period}{Fuel\ Cost\ Incurred\ for\ Power\ Generation}$$

3.5 Auxiliary Consumption

Auxiliary system facility is a major part of a power generation facility and the auxiliary consumption of a power plant depends on its configuration, age and related technical parameters. Purpose of an auxiliary system is to supply power for its own electricity requirements. Auxiliary Consumption Percentage is a very important performance indicator to evaluate the productive output from a power plant.

Normally 0.5% - 2% of power generated is consumed for the auxiliary system in hydro plants while the auxiliary consumption in fossil fuel power plants is 7% - 15% since there are different equipment like feed pumps, cooling water pumps, air fan, etc.

$$Auxiliary\ Consumption = \frac{Gross\ Energy\ Generation\ During\ the\ Nominal\ Period}{Energy\ Consumption\ for\ Auxiliary\ System}$$

3.6 Availability Factor

The evaluation of availability of a power plant is one of the most important tasks at any power station which indicates the fraction of time that it is able to produce electricity over a certain period. To analyze plant availability performance, generation unit outages should be scrutinized to identify the causes of unplanned or forced energy losses and to reduce the planned energy losses. Reducing outages increases the number of operating hours, therefore increases the plant availability factor.

Availability Factor of a generation unit can be calculated using the formula given below.

$$Availability\ Factor = \frac{Duration\ in\ which\ the\ generation\ unit\ was\ available\ for\ opertaion}{Total\ length\ of\ the\ period}$$

4. Special Performance Indicators for Renewable Power Plants

Electricity generation using renewable energy sources is somewhat different from the other conventional methods. These energy sources are freely available in the environment unlimitedly. Therefore some special performance indicators can be defined in the technical, environmental, and sociological point of views.

4.1 Wind Power Generation

- **Specific Energy Production**

  The Specific Energy Production for a wind turbine is calculated using the formula and it can be given in kWh/m^2;

$$Specific\ Energy\ Production = \frac{Total\ Energy\ Production\ During\ the\ Nominal\ Period}{Swept\ Rotor\ Area}$$

- **Noise from Wind Turbines**

  Maximum noise of a wind turbine can be measured in dB from specifically defined distances from wind turbine such as;

  - At the foot of the wind turbine
  - 500m away from the foot of the wind turbine
  - At a standard distance (H + D/2) from the foot of the turbine

    Where;

    H = Height of the turbine tower

    D = Diameter of the circle swept by the turbine blades

- **Birds Fatalities**

  This is to measure the number of birds killed per wind turbine in the reported period

4.2 Solar Power Generation

- **Reference Yield**

This measures the number of hours during which the solar radiation would be at reference irradiance level in the reported period.

$$Y_R = \frac{H}{G_{STC}}$$

Where;
Y_R = Reference Yield
H = In-plane irradiation
G_{STC} = Reference irradiance under Standard Test Condition

4.3 Biomass Power Generation

- **Fuel Moisture**

This measures the moisture (H_2O) content of the biomass as a fraction of the total weight.

$$Fuel\ Moisture = \frac{Moisture\ (H_2\,O)\ Content}{Total\ Weight\ of\ Fuel}$$

- **Ash Emission**

Quantity of the ash emitted, with their compositions could be measured to assess the environmental impact.

4.4 General

- **Contribution to the Reduction of Green House Gas Emission**

This measures the avoided CO_2 emission (in metric tonnes per MW per year), compared to what would have been emitted by a new power plant built in the region, given the same annual production, using the fuel the most likely the future fuel choice, or by the plant most likely to be displaced by the new renewable power plant.

- **Jobs Created by the Plant**

  This measures the number of jobs (direct/indirect) created by a power plant (in number of jobs per MW) for different steps such as manufacture, installation, operation and maintenance.

- **Industrial Safety Accident Rates**

  This measures the number of accidents for all utility personnel permanently assigned to the plant, or fatalities per nominal man-hours worked.

5. Conclusion

The key objective of implementing the performance indicators is, measuring the performance to compare them with other similar networks or systems and to assess the performance improvements attained. The gathered performance measurements are also applicable for Sri Lankan generation and transmission systems.

Whole transmission network in Sri Lanka is owned and operated by Ceylon Electricity Board and most of the data required to compute the aforementioned transmission performance measures, are already recorded by them. Data logging and recording facility should be implemented to obtain the data which is unavailable (Specially power quality measures) to measure the transmission performance.

Most of the data required to compute the generation performance measures of large hydro power plants and fossil fuel fired power plants in Sri Lanka, are already available with the plant operators. Most of the special performance indicators defined for the renewable plants are still in the conceptual stage and therefore a proper mechanism should be implemented to record the data required to compute these performance measures. Perhaps, Data logging and recording facility may be required to be implemented to obtain the data which is unavailable to measure the performance.

Once these performance measures are standardized and computed, they can be deployed not only to monitor the quality and reliability of the electricity supply, but also to measure the performance compared with benchmarks and to illustrate the historical trends.

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