SECURITY AND RELIABILITY CRITERIA FOR ELECTRICITY GENERATION AND TRANSMISSION SYSTEM PLANNING

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INTRODUCTION

In recent years, considerable electricity demand in many countries associated with the high development in various sectors including industrial, tourism, commercial and residential loads, requires power system expansions at all levels, generation, transmission and distribution. In Egypt, for example, three large generating power plants of 4800 MW each have been recently installed [1] and [2]. Also, a large photovoltaic power plant of 1800 MW was constructed at Benban in Aswan [3], in addition to the planned 4800 MW nuclear power station at El-Dabaa and expected increase of renewable energy resources such as wind and solar. This paper describes the main security and reliability criteria for power system planning [4].

The objective is to provide the basic information on the technical design specifications and criteria, technical terms and equipment parameters for successful planning and the requirements of normal case (N), contingency cases (N-1) [5-9]. Additional criteria, that covering aspects of quality of supply which are often contained in the grid code [5] and [6], should be considered in conjunction with the security standards [7-9].

The paper describes the main features, criteria and technical design requirements in the to cope with the development of power grids including connection of large generating plants, transmission system expansion, substation expansions and international connections to external power systems.

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1- Generation Planning Criteria: LOLP, LOLE and reserve margin

2- Transmission Planning Criteria: Normal (N) condition and contingency (N-1) condition

3- Equipment thermal rating

4- Short-circuit levels

5- Dynamic criteria

6- Load shedding

7- Spinning reserve

8- Connection with neighboring countries

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DEFINITIONS

Reliability:

The degree of performance of the elements of the bulk electric system that results in electricity being delivered to customers within accepted standards and in the amount desired.

Adequacy:

The ability of the electric system to supply the aggregate electrical demand and energy requirements of the customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements.

Security:

It is the ability of the electric system to withstand sudden disturbances such as electric short circuits or unanticipated loss of system elements.

1- GENERATION RELIABILITY CRITERION

A- Reliability criterion

The reliability criterion approach is used to determine the installed capacity and reserve margin on the basis of probabilistic analysis of the power system. The Loss Of Load Expectation (LOLE) criterion is the main driver for long term planning of the power system and therefore must be carefully chosen. The general reliability hypotheses for the Egyptian power system planning are summarized as follows. The values that are used for reliability studies are:

- Minimum reserve margin: 15%
- LOLE: 8 hour/year

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- Cables and tie-lines of all voltage levels have an availability of 99.5%.

- Transformers have an availability of 99.5%.

- Reactive compensation means have an availability of 99.5%.

B - Reserve Margin and Installed Capacity Margin

The amount of unused available capability (in MW) of an electric power system at peak load is called reserve margin. Such capacity may be maintained for the purpose of providing operational flexibility and for preserving system reliability. The Installed capacity margin is calculated as the difference between the net peak load demand and the total net installed capacity and is expressed in MW. The Installed capacity margin can also be expressed as a percentage of the net peak load demand.

C- Loss Of Load Probability (LOLP) and Loss Of Load Expectation (LOLE)

The LOLP is a measure of the probability that a system demand will exceed capacity during a given period. The calculation of the LOLP may take also into account the state for which the system will be unable to feed the load demand due to congestion in the network. The LOLE is usually expressed as the estimated number of hours over one year where LOLP is expressed as a probability figure between zero and one or as a percentage. For example; 5 hours per year corresponds to 5/8760 = 0.057%.

Table1 lists the generation reliability requirements in various countries. These include the European Network of Transmission System Operators for Electricity (ENTSO-E), Gulf Cooperation Council Interconnection Authority (GCCIA), Egypt, Kingdom of Saudi Arabia and the Sultanate of Oman.

Table 1- Generation reliability criteria in various countries

ENTSO-E	Two methods (depending on Transmission System Operator): Probabilistic approach: LOLE = 3 hours/year Deterministic criteria: Fixed reserve margin
Egypt	LOLE = 8 h/y + 15% minimum reserve margin
GCCIA	LOLE = 5 h/y (1d/5y) on the interconnected system
KSA	LOLE = 4.8 h/y + 15% min reserve after loss of largest 2 units in isolated areas
Oman	LOLE = 24 h/y

D- Generator Capability Chart

Figure 1 shows a calculated capability chart for a synchronous generating unit. Figure 2 shows the capability chart of a real generating unit in a power station,

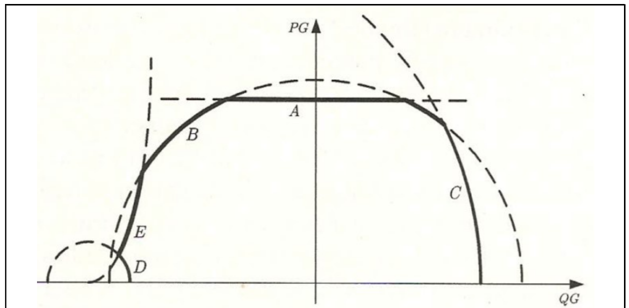

Fig. 1: Generator capability chart [10]

- Part A: Mechanical Source Limit
- Part B: Stator Current Limit
- Part C: Over Excitation Limit
- Part D: Under Excitation Limit
- Part E: Stability Limit

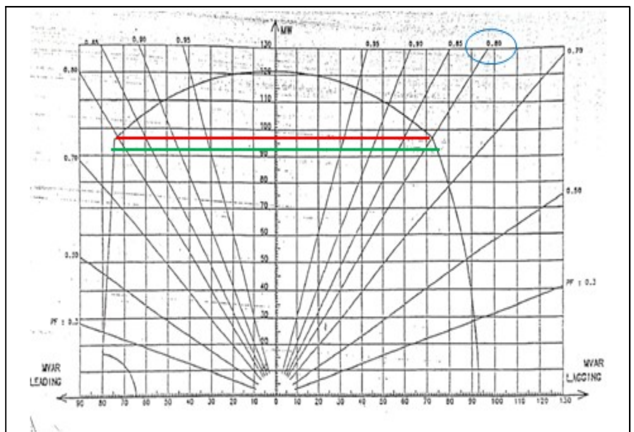

Fig. 2- Capability chart of a real generating unit

2- TRANSMISSION NETWORK PLANNING CRITERIA

A – Normal Condition

The normal condition (base case) represents the system with all elements in service. This is often referred to as N condition. The system must be able to supply all firm demand and firm transfers to other areas. All equipment must:

- Operate within applicable ratings,
- Voltages must be within applicable limits, and
- The system must be stable.

B - Basic Assumptions Related to N Criterion of Transmission Networks:

The rating limits of transmission lines should be intended as maximum permanent currents (or MVA). No overload of the transmission network is allowed. No generator will be above its continuous reactive capability. In normal operating condition, it may be allowed to have long-term overload of transformers up to 10% of nominal current (or MVA). Table 2 shows the normal operating voltage range in the Egyptian power system [5].

C - Normal Operating Frequency Range

The nominal frequency of Egyptian Unified Power System is 50 Hz and its permissible variations range under Automatic Generation Control (AGC) is 50 ± 0.05 Hz. Under normal operating condition the permissible variations range 50 ± 0.2 Hz [5].

Table 2- Normal operating voltage range (±5%) in Egyptian grid

Nominal Voltage (kV)	Maximum Limit (kV)	Minimum Limit (kV)
500	525	475
400	420	380
220	231	209
132	138.6	125.4
66	69.3	62.7

D - Single Contingency

A single contingency, often referred to as (N-1) event, involves the loss of one of the following elements:

- A generator with the associated loss of steam turbine in case of the loss of a gas turbine in combined cycle;
- A circuit of an overhead line;
- A cable circuit;
- A transformer;
- The loss of a cable, a transformer or a single circuit of OHL following a single phase fault cleared in base time (120 ms);
- A compensation element (capacitor bank, reactor or SVC)
- A bus section on transmission system (132 kV, 220 kV, 400 kV or 500 kV)

E - After the single contingency (N-1), the system must respect the following conditions:

- The voltage at all nodes must remain within contingency voltage limits;
- The loading of transmission elements (cables, lines and transformers) must remain within the contingency limits;
- No loss of load allowed;
- The system should be transiently and dynamically stable;
- No activation of defense actions of Under Frequency Load Shedding (UFLS), generator protection, interconnection protections, islanded of generators, etc.);
- The oscillations after the incident have to be correctly damped.

Table 3 shows the voltage limits under contingency conditions in the Egyptian power system. The voltage deviation should not exceed ±10% of the nominal voltage level [5].

Table 3- Voltage limits under contingency conditions (±10%)

Nominal Voltage (kV)	Maximum Limit (kV)	Minimum Limit (kV)
500	550	450
400	440	360
220	242	198
132	145	119
66	72.6	59.4

F – Operating Frequency Range during Contingency

During N-1 contingency conditions: The maximum and minimum permissible frequencies are respectively 50.4 Hz and 49.6 Hz.

In case a sever accident occurs: The frequency could transiently rise to 52 Hz or fall to 47.5 Hz.

Note that if the system frequency rises above 51.0 Hz or falls below 48.5 Hz, manufacturers' instructions concerning the generating units to remain in synchronism with the grid shall apply.

3- Equipment Thermal Loading

Normal operating condition allows a long-term overload of transformers up to 10% of nominal current (or MVA). A temporary (short term) overload (less than 15 minutes) of transformers is allowed up to 20%. In normal operating conditions no overload of the transmission lines is allowed. A temporary overload of the transmission lines generally is allowed up to 20% for 30 minutes. For old lines no overloads are allowed. Ampacity of OHTLs is described in [11].

4 - Short Circuit Levels

The maximum short circuit levels of equipment should be calculated for three phase and single phase to earth faults based on the following assumptions:

- 1.1 p.u pre-fault voltage (according to IEC 60909 Standards)
- Calculated figures should not exceed 100% of switchgear rating
- All generating units and transmission elements are in service during peak conditions

Table 4 shows the short circuit levels in kA at various voltages in the Egyptian power system [5]. Figure 3 shows a typical short-circuit current shape.

The power system fault current levels shall not exceed the values listed in the Table 4. The short-circuit fault ratings for equipment shall not be less than these values.

Table 4- Short Circuit Levels [5]

Nominal System Voltage (kV, r.m.s.)	Short-Circuit Level	
	Short Time Withstand Current (kA)	Peak Withstand Current (kA)
11	25 (3 sec.)	63
22	25 (3 sec.)	63
66	31.5 (1 sec.)	80
132	31.5 (1 sec.)	80
220	40/50 (1 sec.)	125/100
500	40/50 (1 sec.)	125/100

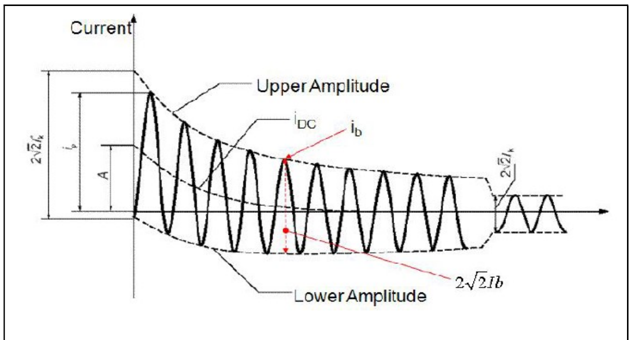

Fig. 3- Short-circuit current

The short circuit levels given above are for a three phase symmetrical fault. Fault level calculations shall be based on the highest voltages at each system voltage level, as defined before.

5- Dynamic Criteria

The system will be considered stable if the following conditions are met:
A – Generator Synchronism
B - System Damping
C - Transient voltage and frequency performance

A -Generator Synchronism

All generators in the system have to remain in synchronism as demonstrated by the relative rotor angles. Neither sustained nor increasing oscillations of the rotor angle is generated for any generator of the system. No loss of synchronism among machines should be detected. No sustained voltage oscillations should be detected on any node.

B - System Damping

The stability curves describing a transiently-limited time domain system trajectory will be visually inspected to insure that the oscillations are damped or at least are as close to 5% damping ratio as is possible.

This value, in fact, is internationally adopted to ensure an acceptable operating condition of the system. A stability simulation is deemed to exhibit positive damping if a line defined by the peak of the machine relative rotor angle swing curve will intersect a second line connecting the valley of the curve with an increase in time. Corresponding lines on bus voltage swing curves will also intersect with an increase in time. A simulation, which satisfies these conditions, will be defined as stable. A simulation, which appears to have zero% damping ratio with acceptable voltage, will be defined as marginally stable.

C- Transient Voltage and Frequency Performance

Minimum transient frequency and duration, maximum transient voltage dips and duration, and post transient voltage deviations should be considered for each of the simulated scenarios. These parameters will be measured at load buses. The minimum frequency and the transient voltage dip should be investigated for each case in order to evaluate the needs for eventually emergency actions. Figure 4 shows the dynamic and steady-state frequency deviations due to generation outage.

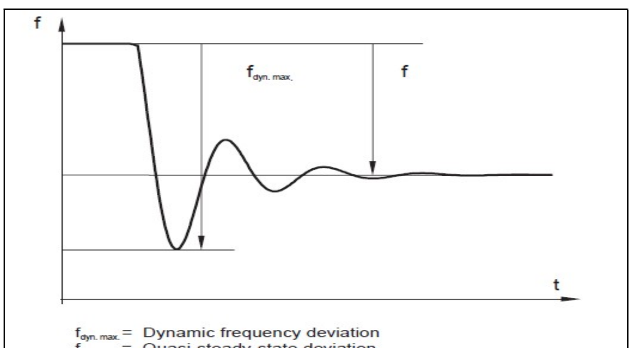

Fig. 4- Dynamic and steady-state frequency deviations

6 – Load Shedding

A - ENTSO-E Recommended UFLS

Figure 5 shows the recommended ENSO-E UFLS [12]. The green band is the most recommended situation, although the yellow one can be reached but could have adverse effects on neighboring systems or on the behavior of the Regional Group Continental Europe (RG CE) wide power system. The border between the green and the red area should be considered as the minimum values.

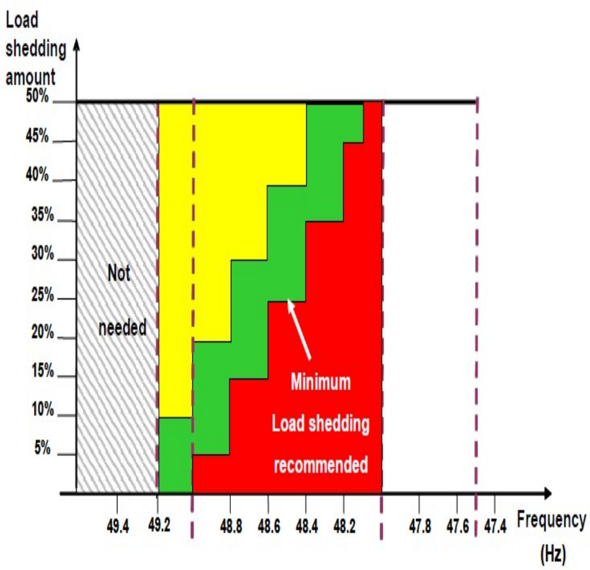

Fig. 5- ENTSO-E recommended UFLS [12]

B - Load Shedding Scheme in Egypt

A load shedding scheme is implemented in the Unified Power System of Egypt [5] based on under-frequency relays and on local measures and actions. This scheme consists of 8 stages, with no time delay and different percentages of total load tripped at each stage, as reported in Table 5.

Table 5- Load shedding scheme in the Egyptian power grid [5]

Frequency (Hz)	Load Shedding (%)
49.2	6
49.1	3
49.0	4
48.9	7
48.8	20
48.7	20
48.65	15% of rest
48.6	15% of rest

7 - Spinning Reserve (SR)

The size of the secured incident corresponds to the largest power loss resulting from a single credible incident (including the loss of a combined cycle: GT + corresponding share of the ST). The spinning reserve should cover the secured incident plus a margin of 10%. The reserve allocated to each unit shall not exceed 5% of the size of the generating unit.

A - Power Reserve Requirement and Criteria

According to the operation rules, in the Egyptian power system, frequency and active power control is provided by the following means:

- Automatic response from generating units operating in a free governor frequency sensitive mode (Primary Reserve);
- Automatic Generation Control (AGC) of generating units equipped with automatic load frequency control (Secondary Reserve).

Table 6 shows example of an operational criterion for operating reserve.

B - Primary and Secondary Responses

Figure 6 shows a typical frequency response. It shows that the primary response must be available within the first 5 seconds after frequency drop incident and should be fully available for at least 25-30 seconds after the event. Beyond that the secondary response should be available and must be available till a maximum of 30 minutes.

Table 6- Operational criteria for definition of operating reserve (EEHC 2008)

Type of Operating Reserve	Value (MW)	Comments
Primary spinning reserve (within 30 sec):		
	250	100 MW Hydro generation
		150 MW Thermal generation
Secondary spinning reserve (within 14.5 minutes):		
In Winter	350	Hydro-Thermal generation
In Summer	175	Hydro-Thermal generation
	175	Interconnection lines
Cold reserve (within 15 minutes):		
	600	Gas Turbines

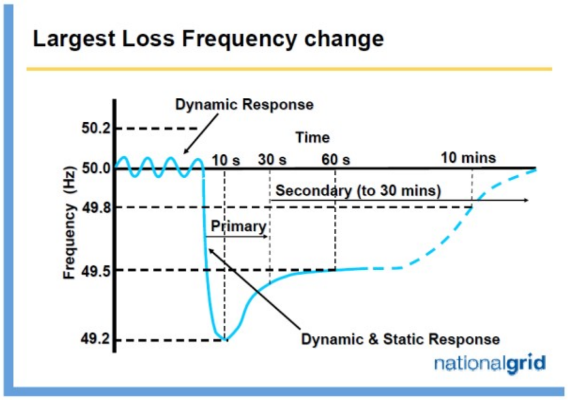

Fig. 6- Primary and secondary frequency responses

8 – Interconnection with External Systems

A – Interconnection sytem with Egypt

The Egyptian unified power system is presently operating in interconnected mode with the neighboring countries:

- Jordan
- Libya
- Sudan

In near future, the Egyptian power system will be interconnected to the KSA system through a DC link to facilitate power exchange of 3000 MW. Interconnection with Sudan (currently through 220 kV ac system) is also expected in near future through 3000 MW link. A link with Europe will be established in future through Cyprus and Greece (via Crete). This will be through a HVDC link sub-marine DC cables. The exchange capacity of the link is expected to be 2000 MW. Figure 7 shows the existing, planned and future international connections with the Egyptian grid [6].

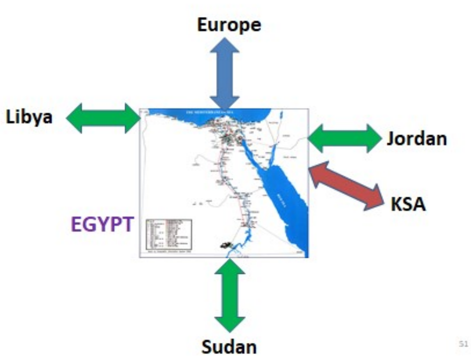

Fig. 7- Interconnections with the Egyptian grid [6]

B- Share of Spinning Reserve in the Interconnected System Operation

Each Transmission System Operator (TSO) should contribute to the SR in accordance with its respective contribution coefficient (Ci):

$$C_i = \frac{P_{gen-i}}{P_{gen-total}}$$

This effectively means that each TSO must maintain a share of the total spinning reserve requirement of the interconnected system which is proportional to its share of the total online generation within the interconnected system at the time of coincident system peak.

C – Egypt-Libya Interconnection

Actually the interconnection with Libya is realized through two 220 kV OHTL starting from Salloum substation in Egypt up to Toubroq substation in Libya. The main parameters of the interconnection lines are:

- Length 257 km
- Rated voltage 220 kV
- Rated power 460 MVA

D - Interconnection with Jordan

The interconnection with the Jordan network is realized through 500/400 kV transformer substation at Taba using autronsformer units installed to create the 400 kV busbar. The interconnection line 400 kV starting from Taba substation in Egypt and ending at Aqaba substation in Jordan is composed of a OHTL and HVAC undersea cable crossing the Aqaba Gulf up to Aqaba substation. The main parameters of the 400 kV Interconnection with the Jordan transmission network are:

- Length 43 km (approximately)
- Rated voltage 400 kV
- Rated power 1780 MVA

E - Egypt-KSA HVDC Interconnection

The Egypt-KSA transmission system comprises of the construction of a ±500 kV, 1300 km HVDC transmission system between Badr substation near Cairo to Madinah East substation and with a tap to Tabuk substation in the K.S.A. Figure 8 shows the planned Egypt/KSA interconnection [13].

Fig. 8- Egypt-KSA interconnection [13]

F - Egypt-Sudan Interconnection

The interconnection with Sudan transmission network has been already operated since 3 April 2020 with 60 MW as a first stage. The interconnector is 220 kV double-circuit overhead transmission line with total capacity of 300 MW when completed (at Sudan Side). The interconnection line starts from Tushka-2 substation in Egypt and ends at Dongola substation in Sudan. The total line length is 170 km (100 km in Egypt side and 70 km in Sudan side). The times of peak demands in Egypt and Sudan are different, thus allowing economic electricity import/export between the two countries. Technical studies are currently being in progress in the two countries to raise the exchange of power to 3000 MW using 500 kV lines in future. This will allow interconnections to other African countries.

G - The Euro-Africa Interconnector Egypt-Cyprus-Crete-Greece – Europe

Euro-Africa will link the electrical systems of Egypt, Cyprus and Greece (via Crete) through sub-marine DC cables and HVDC onshore stations in each country/location, and have a capacity of 2000 MW [14]. Figure 9 shows the future Euro-Africa interconnection.

The Euro-Africa creates an energy bridge between Africa and Europe with a total length of the interconnector being approximately 1648 km, and creates a reliable alternative corridor for transferring electricity to Europe. The Euro-Africa will link the electrical systems of Egypt, Cyprus and Greece (via Crete) through sub-marine DC cables and HVDC onshore stations in each country/location, and have a capacity of 2000 MW.

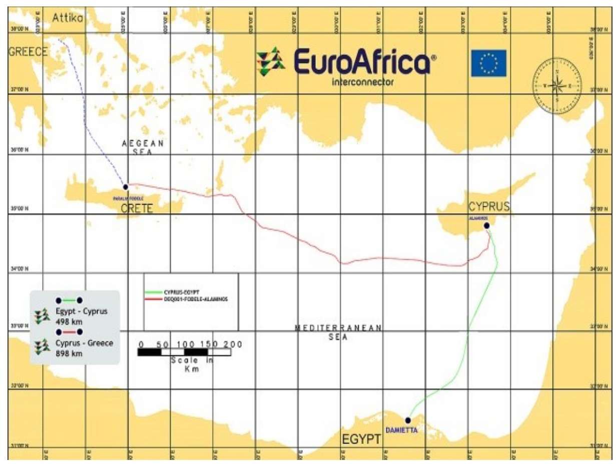

Fig. 9- Euro-Africa interconnection [14]

9 – Right-of-Way Widths

- A minimum right of way width of 70 meters, i.e. 35 meters on either side from the line center, shall be required for 500 kV overhead lines.
- A minimum right-of-way width of 50 meters shall be required for 220 kV overhead lines
- For 66 kV lines 26 meters.

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