# RELIABILITY EVALUATION OF EGYPTIAN AND JORDANIAN INTERCONNECTED POWER SYSTEMS

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## ABSTRACT

The enumeration and Monte-Carlo simulation approaches have been combined in this paper to form a hybrid algorithm for reliability assessment of composite generation and transmission subsystems. The main objective of this approach is to enumerate transmission outages and then sample generation states, conditioned to each enumerated transmission state, to evaluate the annualized reliability indices of the entire system. Within the proposed hybrid algorithm for generation rescheduling, correction of voltage levels or alleviating of component overloading in order to minimize the amount of load curtailment a linear programming model is implemented. This algorithm has been utilized for assessing the reliability of the Egyptian and Jordanian Power Systems as isolated and interconnected system.

## INTRODUCTION

Over the years, two main approaches have been developed for reliability assessment of composite power systems [1-4]. The first approach is based on the successive enumeration of severe/likely system states. The second one is based on a Monte Carlo simulation of system behavior. To identify the system deficiencies and to assess the effect of remedial actions both approaches use a load flow. The major difference between the two approaches is in the process of selecting system states. When a relatively small number of states accounts for most of the probability of the whole state space enumeration based approaches seems to be more efficient. These approaches generally select states in an increasing order of the contingency level. This situation is adequate for transmission reliability studies, in which the network outage probabilities are usually low.

The simulation approaches select states randomly, using the concept of gaming theory and random numbers [5-8]. The process is stopped after a fixed number of simulations or on the basis of statistical stopping rules [8]. The expected value of reliability indices are determined by averaging the obtained indices during each simulation. The major limitation of Monte-Carlo simulation is related to its computational effort, which increases quadratically with the required accuracy of the reliability indices [4].

By enumerating transmission outages and then sample generation outages for each enumerated transmission state, a hybrid algorithm is proposed in this paper to utilize the attractive features of both approaches. As a real example the Egyptian and Jordanian Power System as isolated and interconnected system are considered.

## RELIABILITY MODELING

A power system model is composed of different components, such as generating units, transmission lines and load centers. Each component can be found in one of a set of its possible states. According to the operational behavior of the component these states can be modeled as follows;

### Generating units

The stochastic behavior of a generating unit can be modeled according to its operation mode (base, intermediate or peak unit) by means of 7-states Markov's diagram shown in Figure 1 [5]. The whole state space of this diagram is divided into two partial state spaces defined by "the unit is needed (N)" to cover the load demand, and "it is not nee‘ed (NN)" and is in the standby or repair state. The Markov's model shown in Figure (1) can be explained as follows:

Consider a unit residing in state (R) and is needed either as planned to supply the increasing load or due to forced outage of committed unit. Through a successful planned start-up the unit goes directly to state (B1). However if the unit fails in starting-up, it moves to state (M) for generation reserve activation and then the unit goes to state (A1) for repair. During state (S) the power deficiency is supplied through the spinning or available short-term reserve.

When an operating unit fails, there are two possibilities to depart from its state (B1). The unit is shut down immediately, in which case it moves at first to state (M) and then to state (A1). The shut down is delayed, in which case the unit goes to state (B2) and when the shut down delay is over, the unit moves to state (A1). For both cases repair can be started, and the unit go back to state (S) with repair rate $\mu$ . Repair state appears not only in (N) state space but also in the (NN) state space, since many times the capacity is replaced before a unit is repaired. for steady-state probabilities. The conditional probability $P_r[A1/N]$ of each unit, which represents the

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probability that the unit is not in operation when it is needed to supply system load, can be determined by solving the 7 differential equations describing the whole Markovian process in its steady state as follows [5,6]:

$$P_r[A1/N]=P_r(A1)/[P_r(B1)+P_r(B2)+P_r(A1)+P_r(S)+P_r(M)] \quad (1)$$

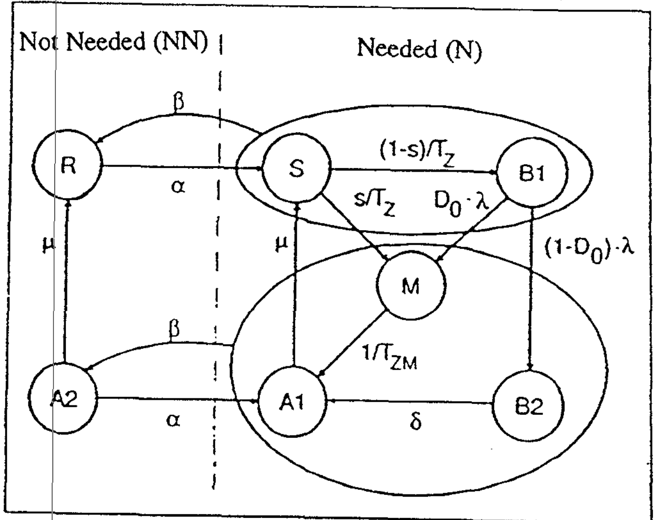


Figure 1. Markov's model for the operating states of generating unit

A1: Repair in (N) A2: Repair in (NN)
B1: Undisturbed operation B2: Disturbed operation
M: Short-term reserve R: Long-term reserve
S: Start of the unit

To calculate $P_r$ [A1/N], the transition rates $\alpha,\beta$ between the two state-space (N) and (NN) are required. These rates depend on the load demand variation and the forced outage of the on-line unit. These transition is governed by the rates $\alpha,\beta$ as explained below.

When the committed units j-1 are not able to cover the system load after forced outage of unit i of the rating $P_{n,i}$, the first reserve block j with a reserve power of $P_{res}$ should be started at time $t_0$. Thus $\alpha_j(t_0)$ equals

$$\alpha_j(t0) = \sum_{i=1}^{j-1} \lambda_i . P_r (P_{out} > P_{res} - P_{n,i}, t_0) \quad (2)$$

The transition of reserve block j from N to NN occurs, when some failed units are repaired and the load could be covered without this block. Therefore

$$\beta_j(t_0)= \sum_{i=1}^{j-1} \mu_i/(j-1) \quad (3)$$

## Transmission Lines

For determining the power flow through the network, each component is represented by its single phase T or Π-equivalent circuit. In order to describe the effect of operational behavior of a component, two different states are considered, namely component in normal(operation) state (B) or component in outage state and is disconnected for repair (state A).

It has been observed that the failure rate of transmission component under adverse weather conditions such as severe storm may be much higher and has relatively short duration than that under normal conditions [7]. Therefore it is important to model separately the component failure rates under normal and adverse weather conditions instead of using one average failure rate. The state diagram of single outage of any line is given in Figure (2).

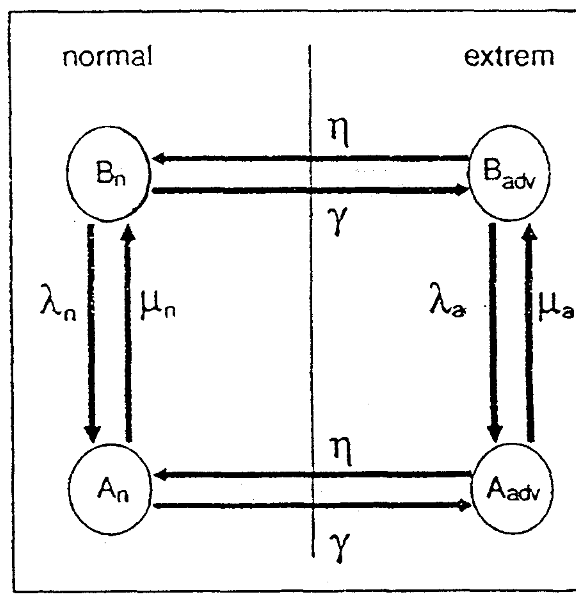


Figure 2. State-space diagram for stochastic single outage of transmission line

$\lambda$: Outage rate $\mu$: Repair rate
B: Operation state A: Outage State
a: Adverse weather n: Normal weather
$\eta$: Transition rate to normal weather
$\gamma$: Transition rate to adverse weather

Due to the low probability of higher order outages, in this study only single and double line outages are considered.

The state diagram for overlapping two stochastic outage and dependent double line outage are given in figure (3).

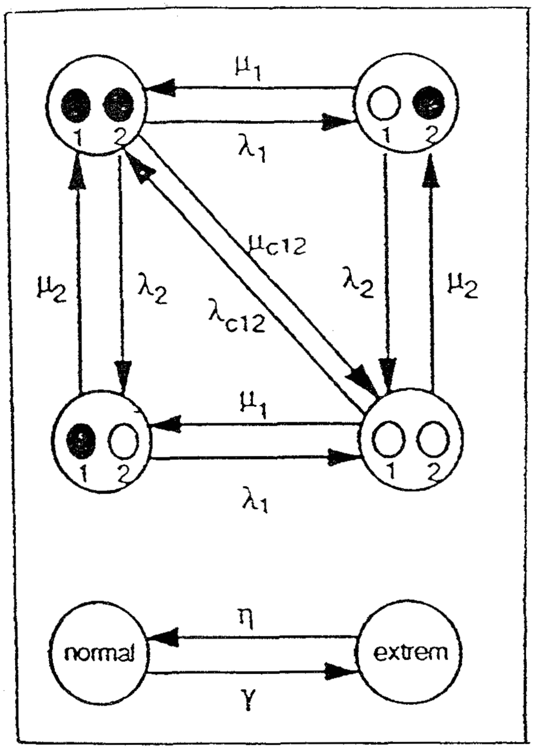


Figure 3. Markov's model for double line outage

●: Operation state O: Failure state
$\mu_1$: Repair rate of line 1 $\lambda_2$: Failure rate of line 2
$\lambda_{c12}$: Rate of dependent double line common failure
$\mu_{c12}$ Rate of dependent double line repair
$\eta$: Transition rate to adverse weather
$\gamma$: Transition rate to normal weather

Given the state of each component $x_i$, it is possible to calculate the probability of the transmission -state vector, $P_r(x)$ as the product of the probabilities associated with each component state as follows:

$$P_r(x) = \prod_{i=1}^{n} P_r(x_i) \quad (4)$$

**Load Modeling**

The influence of load variations on reliability indices can be visualized by Figure (3), which represents the load supply capability of a given system under normal and contingency conditions. As shown in Figure (4) the different contingencies with the same duration may lead to different energy interruptions, depending on the rate of change of load demand.

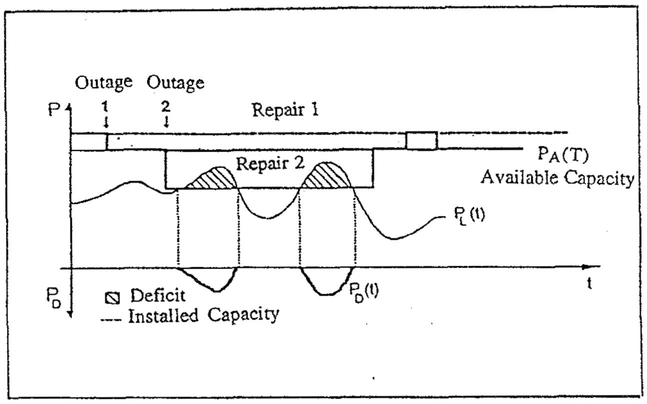


Figure 4. Effect of load variation on the duration and frequency of supply interruption

## HYBRID RELIABILITY ALGORITHM

At first maintenance scheduling, energy planning and then unit commitment for the studied time horizon of one year are carried out. Using the determined unit commitment the operational behavior of generating units can be simulated according to their operation mode. The proposed hybrid algorithm is composed of the following steps:

**Step 1:**
Read the system configuration, hourly load levels and the required input parameters, such as the number of samplings and the convergence tolerance.

**Step 2:**
From the annual record of the load variation define the considered load level.

**Step 3:**
Select transmission subsystem states at the defined load level of step(2). The selection of these states is carried out by successive enumeration of line outages based on their severity/likelihood conditions.

**Step 4:**
For each defined transmission state, the states of the committed unit states are modeled using Monte-Carlo simulation. A uniformly distributed random number $u_i$

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between [0,1] is obtained for the i th generator. If $u_i < 1-Pr[R1/N]$ the generator is in normal state. If the time duration of the considered transmission state is greater than the required time to start cold unit the system performance depends only on the available generation capacity otherwise it depends on the generation state before outage.

**Step 5:**
Check the adequacy of the selected system state using fast decoupled a.c. load flow, i.e. verify whether the selected configuration of generators and network is able to supply the load without violating operating limits. These security constraints are basically the operating limits which have to be satisfied for normal operation of the power network such as voltage magnitude, line flow and generation constraints.

Voltage constraint: Operating limits are imposed on the voltage magnitude of PQ buses

$$V_{min} < V < V_{max} \quad (5)$$

Flow constraints: The thermal operating constraints of transmission lines and transformers limit the amount of current flow to

$$I_i < I_{i,\,max} \quad (6)$$

Generation constraints: The real power generated at the generating bus is limited by

$$P_{G,i,min} < P_{G,i} < P_{G,i,max} \quad (7)$$

For such cases with constraint violation, the corrective actions such as the generation rescheduling and tap changing are taken into consideration to keep the system in its normal operation state. If it is not possible to overcome this problem the amount of load curtailment $P_D$ should be minimized by combining the linear programming relaxation technique with the dual simplex method [5,8].

**Step 6:** During the observed time horizon $T_n$ update the estimates of reliability indices such as the probability of load curtailment $P_{r,D,i}$ at $n_D$ busses, their expected duration $E(T_{DC})$ and the expected unserved energy $E(W_{DC})$ using the following equations:

$$E(T_{DC}) = T_n \cdot \sum_{i=1}^{n_D} P_{rD,i} \quad (5)$$

$$E(W_{DC}) = T_n \cdot \sum_{i=1}^{n_D} P_{r\,D,i} \cdot P_{D,i} \quad (6)$$

If the prespecified sample size of the generating units is reached and the prespecified enumeration of contingencies in the transmission subsystem is exhausted go to the next step. Otherwise go to step 3.

**Step 7 :** If all load levels are not considered, go to step 2 again. Otherwise print the annual reliability indices described in step 6 by weighting the obtained indices by the corresponding load probabilities.

## CASE STUDIES

### Electrical Power System in Egypt

The electrical power in Egypt is produced from the available Hydro and conventional thermal resources. The Hydro Power Stations on the river Nile consist of the following plants: High Dam Power Station of total installed capacity of 12x175 MW. Aswan Dam (1) power Station of total installed capacity of 345 MW. Aswan Dam (2) power Station with total installed capacity of 270 MW. The thermal generating stations including steam and gas turbine plants with a total capacity of 9195 MW (in 1993), distributed among the five distribution zones of electrical energy in Egypt [9].

The ultra and high voltage electrical network in Egypt are considered as the main vessels for transmitting the electrical energy to load centers, through 500, 220, 132, 66, 33 kV substations. The 132 kV and 33 kV networks are concentrated in upper Egypt, while the 220 and 66 kV networks are concentrated in lower Egypt. The electrical energy is transmitted via single circuit 500 kV OHTL network of total length 1594 km, double circuit 220 kV OHTL network of 4821 km length, in addition to 132 kV OHTL and to low and high pressure oil filled cables (132) in upper Egypt.

The electrical demand growth during the period ( 1983-1993) was about 7 % per annum on average. The expected annual growth for electrical demand for the period (1993-2000) is 6.4 %. The maximum peak demand in year 1993 reached 7717 MW.

The reliability indices of the Egyptian power system, classified according to their causes in generation and transmission subsystems, are given in Table 1. The test results indicated that the probability of power deficiency at peak load due to the transmission network is about 6.4 times greater than that of generation subsystem. This can be attributed to transmission capacity limitation of 500 kV line between High Dam and Cairo substation to 1800 MW from the stability point of view for the unified system. Single line outages represent 16 % of the supply interruption, while double line outages causes 3%. The contribution of 220 kV network of lower Egypt at the supply interruption is very small ( 2%) compared to 500 kV line with (82.6%). This small part is due to relatively light loading of 220 kV meshed network in normal operation.

| Reliability Indices | $P_r(D)_{max}$ % | $E(T_{DC})$ h/year | $E(W_{DC})$ MWh/year |
|---|---|---|---|
| Generation | 0.55 | 2.31 | 1744.68 |
| Transmiss. | 3.54 | 15.18 | 5114.57 |
| Total | 4.09 | 17.49 | 6859.25 |

Table(1):Reliability Indices of Egyptian Power System

$P_r(D)_{max}$ : Maximum probability of load curtailment
$E(T_{DC})$ : Expected duration of load curtailment
$E(W_{DC})$ : Expected value of unserved energy

## Electrical Power System in Jordan

The electrical power in Jordan is produced from the following thermal power stations: Aqaba thermal power station in south of Jordan with a total capacity of (2x130 MW). Jordan Electricity Authority is now considering the addition of another 2x130 MW units to be in operation in 1997. Hussein thermal power station, near Amman has a total capacity of 363 MW. Risha power station is in the east ( at the border with Iraq) with 4x30 MW gas turbines [10].

The transmission system consists of about 1500 km of double circuit 132 kV overhead lines extending all over Jordan. There is one double circuit line of 400 kV extending from Aqaba thermal power station to Amman south substation in the center of the loads, with a total length of 325 km [10]. This line is operated now at 132 kV and will be uprated to its 400 kV designed voltage by the end of 1996 through constructing two 400 kV substation at Aqaba and Amman South [10].

The electrical demand growth during the period (1983-1993) was about 8.7 % per annum on the average. The expected average annual growth for the electricity demand for the period (1993-2000) is 5.6 %. The maximum peak demand in 1993 reached 717 MW.

| Reliability Indices | $P_r(D)_{max}$ % | $E(T_{CD})$ h/year | $E(W_{DC})$ MWh/year |
|---|---|---|---|
| Generation | 4.25 | 13.98 | 1442.95 |
| Transmiss. | 0.05 | 0.35 | 110.04 |
| Total | 4.30 | 14.33 | 1652.99 |

Table (2) : Reliability Indices of Jordanian Power System

The reliability indices of the Jordanian power system, classified according to their causes in generation and transmission subsystems, are given in Table 2. The obtained results indicate, that the transmission network plays no significant roll (about 1%) by supply interruptions.

## Interconnection of Egyptian and Jordanian Systems

The interconnection involves a 310 km link between the North-West of Suez and south of Aqaba with an interchanged power up to 600 MW (future size of largest generating unit in Egypt). This link would be mainly consist of 500 kV OHTL, interrupted by Suez Canal crossing by 2 km underground cable, the Gulf of Aqaba crossing by 12 km submarine cable then an OHTL to Aqaba thermal power station.

Interconnecting both systems results in improving their reliabilities. This can be attributed to the replacement of generation deficiency and relieving lines overloads through power interchange in emergency conditions. The reliability indices for an interchanged power of 600 MW are given in Tables (3) and (4). Compared to the base case without interconnection the probability and duration of Power deficit in the Egyptian power system decreased from 4.09 to 0.61 % and from 17.49 to 5.18 h respectively. Moreover, the amount of EENS decreased from 6859.25 to 2081.60 kWh. Table (4) indicates that, the great benefits due to interconnection is achieved in the electric power system of Jordanien. This can be explained by high power interchange/load demand of 85 % in Jordan compared to that of 8 % in the electric power system of Egypt.

| Reliability Indices | $P_r(D)_{max}$ % | $E(T_{DC})$ h/year | $E(W_{DC})$ MWh/year |
|---|---|---|---|
| Generation | 0.48 | 2.28 | 1584.02 |
| Transmiss. | 0.12 | 1.07 | 497.58 |
| Total | 0.60 | 3.35 | 2081.60 |

Table (3): Interconnection Effect on Reliability Indices of the Egyptian Power System

| Reliability Indices | $P_r(D)max$ % | $E(T_{DC})$ h/year | $E(W_{DC})$ MWh/year |
|---|---|---|---|
| Generation | 0.05 | 0.57 | 26.55 |
| Transmiss. | 0.02 | 0.18 | 11.82 |
| Total | 0.07 | 0.75 | 37.37 |

Table (4) : Interconnection Effect on Reliability Indices of the Jordanian Power System

Table (5) shows the obtained results considering both interconnected systems as one system. The improvement

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in reliability indices of the whole system is smaller than that given in Tables (3) and (4). This can be attributed to the effect of simultaneous outages in both systems, where the available interchanged power in such conditions is less than 600 MW. The required computations was carried out using VAX 4000 model 60 and CPU time for the interconnected system equals 15 minutes.

| Reliability Indices | $P_r(D)_{max}$ % | $E(T_{DC})$ h/year | $E(W_{DC})$ MWh/year |
|---|---|---|---|
| Generation | 0.51 | 2.42 | 1323.15 |
| Transmiss. | 0.86 | 4.67 | 1236.68 |
| Total | 1.37 | 7.18 | 3559.83 |

Table (5): Reliability Indices of the Whole System

## 5. Conclusions:

In this paper a hybrid algorithm for reliability evaluation of interconnected power system was proposed. The generation outages are simulated using Monte-Carlo technique, after enumerating the severe network states. Moreover, the effect of forced outages on the different load buses were mathematically estimated using fault effect analysis, taking into account the available corrective actions.

The Unified Egyptian and Jordanian Power System have been modeled and their annualized reliability indices were evaluated using the proposed hybrid algorithm. The test results indicated a strong influence of transmission subsystem, especially of 500 kV line, on the reliability of supply for the Egyptian. On the other hand, the generation subsystem has a great impact on the reliability of supply in Jordan

In order to improve the system reliability the effect of interconnecting both systems has been studied . This interconnection resulted in reduction of the expected unserved energy by factor of 6.3.

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