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Reliability/Cost Tradeoff Evaluation for Interconnected Electric Power Systems

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Abstract: This study is attempting to explore the effects of electric power systems interconnection upon enhancing their overall reliability levels and reducing their fixed and operating costs. To justify the practical and tangible benefits of this work, the proposed approach has been applied to three electric utilities in the Western part of Saudi Arabia, namely, Jeddah, Mecca, and Taif. In this study, unified measures for reliability evaluation, based on efficient and practical techniques, have been developed and applied to these three systems before and after interconnection. By applying these measures, it has been possible to evaluate the economical and technical advantages which may accrue resulting from the mutual interconnection among those three electric utilities.

Keywords: Planning, Power, Energy, Outages, Interconnection, Cost, Reliability.

1. Introduction

Power system interconnection can be effectively implemented to simultaneously enhance overall system reliability *and* reduce its operating reserve overhead. Differences in the interconnected systems regarding load requirements and capacity outages lead to opportunities for the systems to back each other when the need arises, such as in cases of severe outages, capacity deficits and load shedding. Additionally, it permits each system in the interconnection to have a reserve capacity less than that of being dispersed and isolated.

From a technical perspective, the mutual reliability and cost benefits that could be attained from systems interconnection efforts primarily depend on the operating reserves, and operating conditions of each individual system. Among the owners of the systems, the mutual agreements between them drive the realization and measurement of the expected benefits. This has driven the development of methodologies to accurately model and evaluate reliability and cost.

To establish target reliability levels for systems interconnections, reliability criteria must be followed. The adopted criteria are consistently referenced to analyze future reliability levels and compare them with feasible alternative expansion plans.

2. Previous works in the nature of this study

The following part exhibits some pertinent works that have been done in the similar nature of this study.

It has been evidenced that the early advent of reliability evaluation of power systems has been evolved by the first pioneer in this field, namely, Roy Billinton [1].

In [2,3], the authors discussed in their works the six Gulf states networks interconnection. The outcomes of the authors' studies showed the benefits of this interconnection in terms of reinforcement to their individual systems and gaining savings in installation and operation costs.

In [4], the author presented interconnection security issues which can be included in quantitative power system reliability assessments, influencing cost/benefit tradeoff evaluation of system generation expansion planning in the context of interconnected power systems.

In [5] the author asserts the requirement, especially in developing countries, to interconnect isolated utilities systems in each individual zone as a previous step toward their eventual future interconnection with adjacent states.

In [6], the author estimates what the Republic of Korea may gain in environmental benefits resulting from the connection among Northeast Asian countries. Reductions in TCE (tons of carbon equivalent) and in CO_2 taxes, are projected environmental benefits resulting from

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the author's analysis of the system interconnection scenarios.

In [7], A methodology based on a probabilistic modeling has been elaborated by the author to describe the "Interconnection Capacity Assistance" (ICA) that can be mutually interchanged between the electric systems in times of emergencies, lack of power, and reserve deficits.

From preceding review of existing research applying reliability evaluation in power system interconnections, it becomes evident that reliability is a prime concern that must be observed when planning, installing, and interconnecting electric power systems. Reliability criteria must be adopted to establish target reliability levels. The criteria are then consistently referenced to evaluate future reliability levels and compare the alternatives with feasible and appropriate expansion plans.

3. Pertinent Reliability Indices of Power Systems

A) Loss of Load Expectation

The most widely reliability measures accepted and used by the power systems planners is the Loss of Load Expectation, LOLE index,

This index has been defined [1] as: "the expected number of days in the specified period in which the load levels will exceed the available system capacity". For the evaluation of this index, two models are needed, namely, the Load Duration Curve (LDC) and the other is the Capacity Outage Probability Table (COPT). The LOLE can be expressed as [8]:

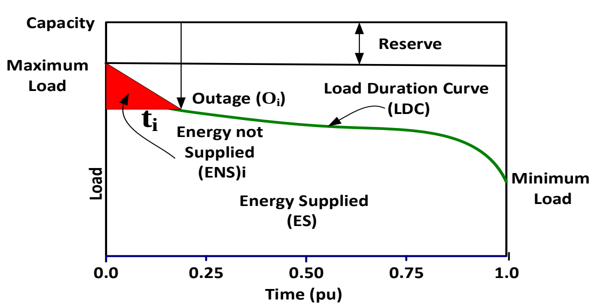

Fig. 1 Load Duration Curve displaying various load-related variables

$$LOLE = \sum_{i=1}^{n} t_i \cdot p(O_i) \ (d/y) \ \ (O_i > C) \qquad (1)$$

Where

t_i: *time duration of that severs outage* O_i

$p(O_i)$: *probability of loss of load due to the* i^{th} *severe outage of size* O_i.

n: *total number of severe outages ocurred during that period considered.*

C: *system capacity.*

B) Expected Energy Not Supplied (ϵENS)

As the unserved energy is being lost energy due to power outages occurrences, it causes immense damages and heavy losses to the all customers and may spread to the entire society. Therefore, this index can be shown as [9]:

$$\epsilon ENS = \sum_{i=1}^{n} (ENS_i).p_i \quad MWh/y \ \ (O_i > C) \qquad (2)$$

C) Energy Index of Reliability (EIR)

The ratio of expected energy not served (ϵENS) to the system Total Energy Demanded (TED), which is the area under the LDC, can be determined as:

$$\epsilon ENS_{pu} = \frac{\epsilon ENS}{TED} \qquad (3)$$

In fact, the ϵENS_{pu} is a very small ratio, therefore, it can be subtracted from 1 to yield more comprehended number, and it can be expressed as:

$$EIR = 1 - \epsilon ENS_{pu} \qquad (4)$$

4. Costs Aspects of Electric Power Systems

The general costs normally associated with electric power generation and operation can be classified in the following categories:

A) Fixed Cost:

In power systems, the fixed cost (FC) means the cost of investments in erecting power stations, purchasing equipment, installing auxiliaries and reinforcing networks. These costs can be stated as follows:

$$FC_T = \sum_t \sum_k (CC_k \cdot CAP_k \cdot NU_k)^t \qquad (5)$$

B) ***Variable Cost***:

There is another cost related to operation, namely, Variable Cost (VC). These costs include mainly fuel, interim maintenance and spare parts, and can be expressed as:

$$VC_T = \sum_t \sum_k (VOM_k \cdot CAP_k \cdot NU_k)^t \qquad (6)$$

Now, the above two costs mentioned in A and B cab can be summed up together and considered as the System Cost (SC) as expressed in the following equation:

$$SC_T = FC_T + VC_T \qquad (7)$$

C) ***Outages Cost***:

Undesired loss of power can be caused by severe power outages that may occur abruptly and unexpectedly. This is shown in Fig. 1 as the red-shaded area and designated as the Energy Not Supplied "ENS". To evaluate the outage cost

(OC) associated with this type of unsupplied energy due to severe outages) and designated as outages cost OC), it can be estimated as follows [10]:

$$OC_T = \sum_{t} (\epsilon ENS \cdot OCR)^{t} \quad (8)$$

Where,

CC_k : *capital cost of unit of type k*

CAP_k: *unit capacity added to the system on type k.*

NU_k: *number of unit(s) added to the system of type k.*

VOM_k: *variable operation & maintenance to unit Of type k (mainly cost of fuel).*

ϵENS_t: *expected energy not supplied to the consumers due to power outages (kWh lost).*

t: *interval period of time considered in the Planning horizon.*

T: *total number of years in the planning horizon.*

OCR: SR/kWh.

It is realized that system cost (SC_T), as appeared in Equation (7) constitutes the size of capital investment expended in capacity installations (FC) as well as the cost of fuel consumed due to generation facilities operation and maintenance (VC). The more investment in system cost reflects in enhancing and upgrading the reliability level of power system by reducing the outages occurrences that lowering system reliability risk level and hence mitigating their costs (OC) exhibited in Equation (9).

From scrutinizing the nature of the two costs, namely, system cost and outage cost appeared in Equations (7) and (8) respectively, it is realized that these costs are antagonizing in their nature and impact upon system reliability level. Therefore, these costs can be combined and consolidated as the Overall System Cost (OSC) and given in the following equation:

$$OSC_T = SC_T + OC_T \quad (9)$$

The above equation can be utilized and applied in the process of seeking the most opimal reliability risk index that can be reached by compromising between thes two prominent costs, i.e. system cost and outages cost. These aspects will be displayed and discussed later on.

5. APPLICATIO OF RELIABILITY ASPECTS IN POWERSYSTEMS INTERCONNECTION

Powe system interconnection is considered to be vital and essential issues for most of countries and utilities in their expansion planning and budgetting. The interconnection between power systems can be within the country territory or with neighboring countries via nationl grids.

Fige. 2, portrays the configuration types of systems interconnection.

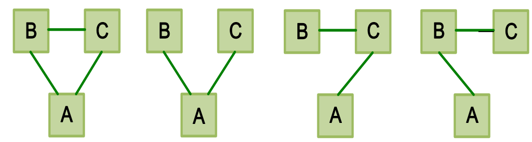

Figure 2. Arrangements Types of interconnected systems

A. *Systems are being interconnected with independent loads*

Suppose that there are two isolated power systems, namely, A and B and each one is having its own generation and loads with the following two postulates:

- The capability of each system to assist the other during severe outages and lack of reserve if there is an available and adequate reserve capacity.
- A connecting Tie-Line to transfer the Assistance Capacity (AC) to the assisted system.

The above two points are depicted in Fig. 3, where it shows that, in case of existing tie-line, one system can assist the other with an "Assistance Capacity, AC" that is available and adequate in its reserve.

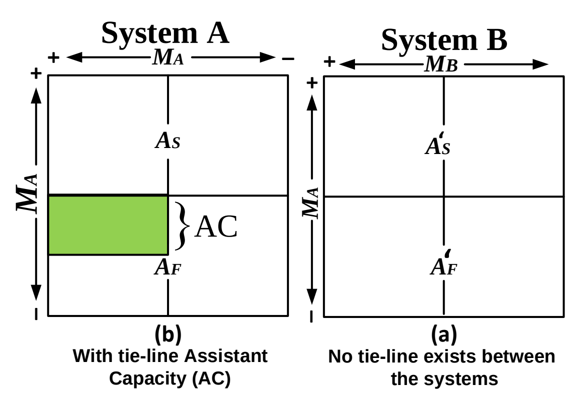

Figure 3. Assistant Capacity (AC) transferred between systems in cases of emergencies

For the purpose of this study, a process based on the methodology described in [11] which employed the total system capacity assistance as an Equivalent Assisting Unit (EAU) for the interconnected systems. This process is exhibited in Fig. 4, where it involves and simulates the techniques and assumptions that have been proposed and demonstrated in this study.

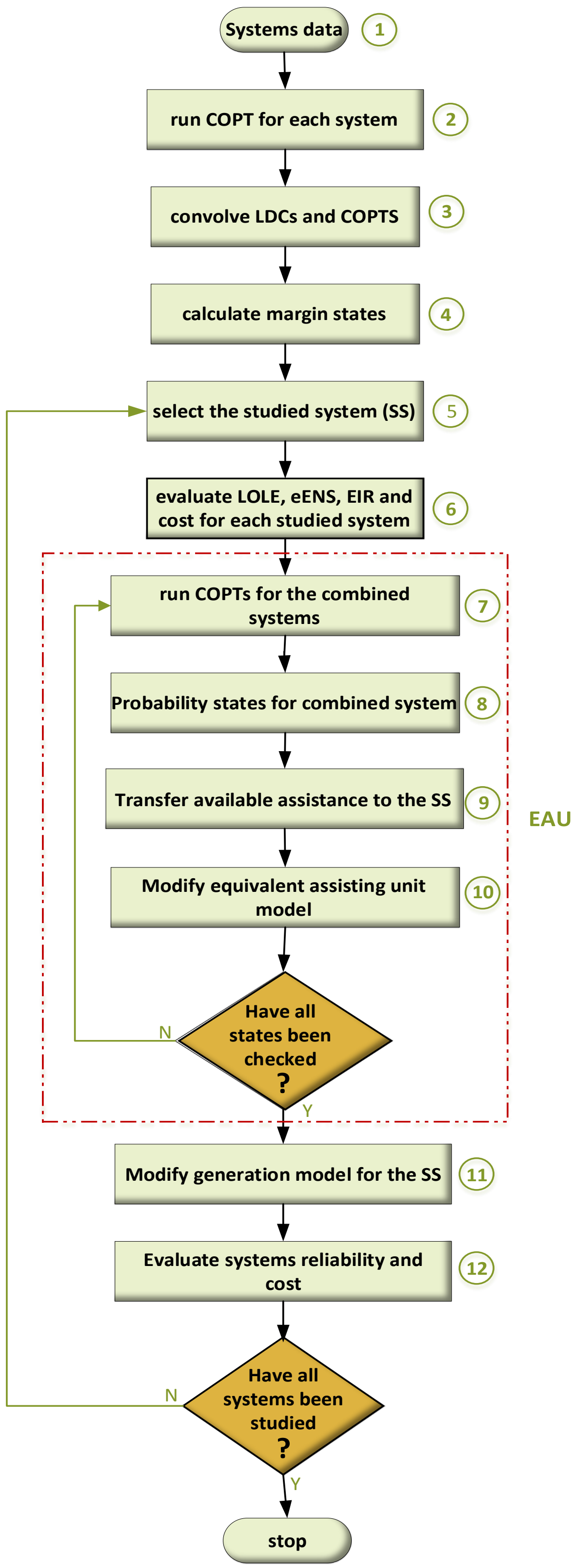

Figure 4. Methodology process for the proposed study

6. Methodology Application to Existing Systems

The proposed methodology, presented in the previous sections, has been substantiated and then practically applied to existing utilities that serve major metropolitan areas in the western zone of the Kingdom of Saudi Arabia, namely, Jeddah, Mecca, and Taif and designated in this study as (A), (B) and (C) respectively. These cities are characterized as having multiple industrial, governmental, and agricultural projects, in addition to high population density, all driving rapid demand growth.

The generation expansion planning that this study considers extending over a duration of five years (2017 – 2022), to schedule the timings of capacity additions and evaluates the reliability risk-levels of the power systems prior and after the interconnection. In the next section, the economic and technical merits that could accrue resulting from systems interconnection will be explored and investigated.

A. *Technical merits of Interconnect Power Systems*

The eventual target of this proposed study is to investigate and assess the reliability risk-level of each individual power system under study, designated as A, B, and C, before and after the interconnection process over the prescribed period.

The three power systems (A, B, C) were subjected to a reliability evaluation process employing the popular reliability index Loss of Load Expectation (LOLE) that appears in Equation (1). The evaluation outcome is depicted in Fig. 5, where it shows noticeable improvements in reliability levels for each system after being interconnected rather of being isolated.

To substantiate and ensure the upgrading and improvements in the reliability levels of electric power utilities under study as a result of interconnection, the other reliability measures stated in this study, namely, ϵENS and EIR (Equations 2 and 4) were applied and investigated. Systems A was chosen to demonstrate the effects of systems interconnection upon the ϵENS. Fig. 6 displays the reduction in the expected energy not served (ϵENS) as a result of the interconnection between them. The *EIR* index is also examined with system C, with the results displayed in Fig. (7) which clearly shows the rise in the reliability indicator and decrease in the energy loss after interconnection between the systems occurs. This indicator should decrease as the ϵENS decreases due to more available capacity streaming through the tie-line interconnection.

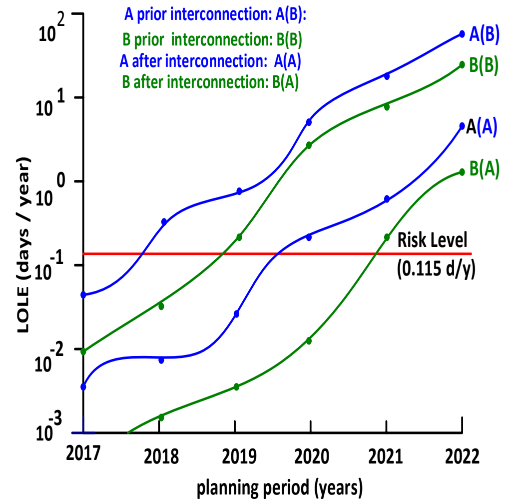

Figure 5. LOLE risk-levels for the three system prior and after being connected

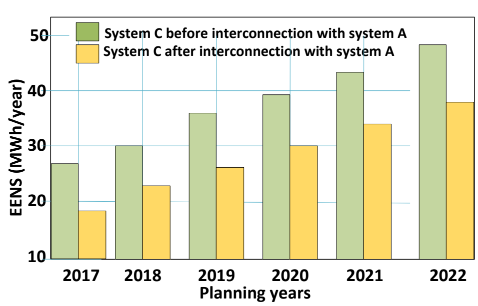

Figure 6. ϵENS prior and after interconnection

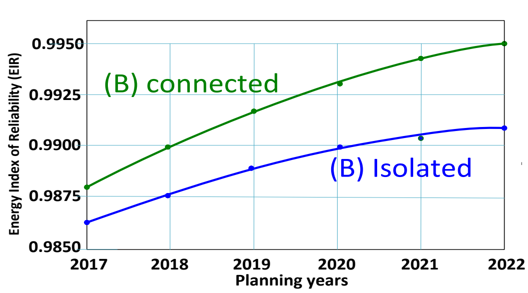

Figure 7. EIR index prior and after interconnection

B. *Economical Merits of Interconned power systems*

This part of the study aims to assess the economic advantages that the interconnection of the three systems may yield. A study has been conducted of the 5-year period starting 2017 (2017-2022). The *LOLE* index has been prescribed to be set at 0.115 days/year. This number is, in fact, not fixed or constant, but it is a management decision and varies according to specific cases and situations. For instance, If the case under study concerns a heavily industrialized country, it is an imperative to be lowered accordingly. To proceed for exploring possible economic merits of systems interconnection, the three systems have been studied utilizing Equations (6), (7) and (8). Therefore, for the envisaged 5-year plan, the savings in system costs (fixed, variable and outage costs) can be estimated (from Fig. 8) as 41%, 37%, 20%, 28%, 41% and 35% for systems (A), (B) and (C) [i.e. Jeddah, Mecca, and Taif] respectively. Furthermore, these attained savings came due to the improvement in the three-systems reliability risk-level as has been analyzed and predicted in the preceding sections.

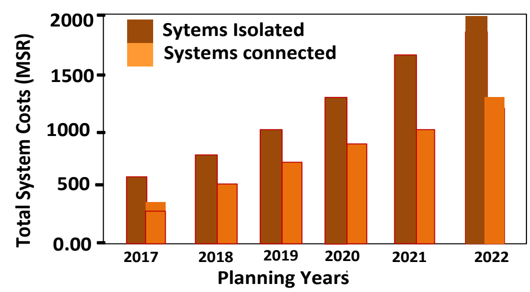

Figure 8. Cost (MSR) for isolated and interconnected systems

7. Planning for Optimization of Power Systems

The ultimate target of power systems planners in the concerned entities and sectors is to achieve the most optimal system plans in terms of adequate supply and reasonable costs.

For this final portion of the study, it is an essential to consider and implement the concepts of outage cost (OC) discussed and elaborated in Section 4 (part C and Equation. (9) as well as the developed process exhibited by Fig, 4. Accordingly, system (A) has been selected for this application using all the reliability and economic concepts and criteria demonstrated in various sections of this study.

The results of this application are portrayed by Fig. 9 which indicates that both system cost (SC) and outage cost (OC) have some sort of antagonizing and contradicting nature with reliability-level variations. It is evident that the system cost increases with higher reliability (i.e. less number) and vice versa, as the outage cost decreases with lower reliability and vice versa.

For this application, the overall system cost (OSC), expressed by Equation 9, indicates the least level of cost corresponding with the most optimum reliability level that can be reached and verified which in this case to be within the range of 0.15 and 0.20 days/year.

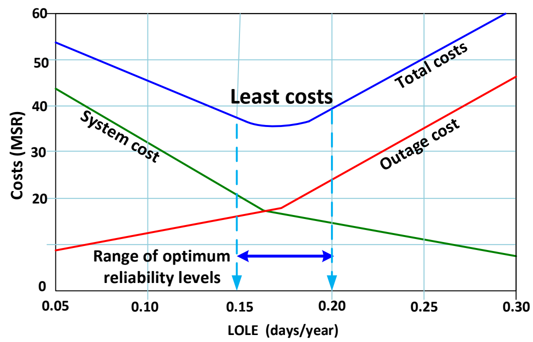

Figure 9. Variations of system costs vs. reliability levels

8. CONCLUSION

This study presents, analyzed and discussed methods, techniques and criteria pertinent for reliability-cost tradeoff for power systems planning in cases of being isolated and interconnect. Reliability criteria and economical measures were applied in both cases. It has been evidenced by the study results that power system reliability-cost tradeoff is an intricate nature and sensitive issue and hence ought to be carefully and wisely performed embraced in power system planning and interconnection. This performance will enhance system reliability levels, mitigating power outage risks, limiting service cease, reducing system cost, and hedge against possible energy curtailment.

The outcome of such a study is invaluable to those engineers and executives who are working with electric utilities and management and planning sectors and departments.

Finally, it is hoped that this type of study is useful to the existing GCC tie-line currently connecting the six Arabian Gulf states.

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