Reliability evaluation for different power plant busbar layouts by using sequential Monte Carlo simulation

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A B S T R A C T

In deregulated electricity market environment, the power system works with lower stability margin due to demand fluctuations. Therefore, in restructured power systems all generation companies attempt to increase reliability of their own power plants. The arrangement of the busbar layouts in power stations has a great effect on the power system reliability. This paper develops a sequential Monte Carlo simulation (SMCS) to evaluate the effect of generator breaker and bus-section on the reliability indices of one and half and two-breaker busbar layouts. Karun III power station layout in Iran national grid (ING) is considered as a real world system case study. The most commonly used reliability indices such as loss of load expectation (LOLE), expected energy not supplied (EENS) and expected load curtailment (ELC) are used to evaluate the reliability in this paper. Economic and technical evaluations of reliability indices variation in presence of generator breaker and bus-section are presented. Simulation results show that how variation of forced outage rate (FOR) of generator and generator breaker affect on the reliability indices.

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1. Introduction

In modern electric power systems, the peak load value is usually increased and stressed conditions are occurred more than past [1–3]. In this condition, the occurrence of any contingency may lead to instability. Power plants are the most strategic points in power systems and their reliability has a great effect on the power system performance. Therefore, in recent years, studying the performance of power plants with the highest possible availability has become one of the interesting subjects for researchers [1]. Various factors affect on the reliability of an electrical substation or switchyard facility, one of them is the arrangement of switching devices and buses. For the sake of busbar layouts effects on the reliability, some modifications for busbar schemes have been suggested [1]. Also, additional parameters such as maintenance, operational flexibility, relay protection, cost and line connections should be considered in reliability assessment of different substation configurations. The effect of substation type, from view of insulation, for air insulation substation (AIS) and gas insulation substation (GIS) has been investigated in [4]. In [5] the availability of various power substation architectures has been compared. Also reliability of eight basic industrial substation configurations is analyzed in [6]. The effect of generator breaker, power plant transformers including main transformer (MT), unit transformer (UT), station transformer (ST) and their numbers on the reliability of different types of busbar layouts is evaluated in [4]. In [7], an approach to incorporate switching actions with disconnects switches and circuit breakers in the reliability evaluation of substation topologies are presented. In [8] the impacts of elements active and passive failures on the performance of power plant layout are examined. A tie-set based comprehensive methodology for quantitative reliability assessment of substation automation systems is presented in [9]. The influence of HV breakers advanced auto-diagnostic systems for improving the reliability of power-plant layout is discussed in [10]. As shown in [11], the generator breaker has a great effect on the fault occurrence in power transformer. It should be noted that, using the generator breaker improves the power plant availability and provides the possibility of direct plant auxiliaries to-be-fed from the main net (EHV, transmission system) which is more reliable than the reserve net (local sub-transmission system). Moreover, interruption due to short circuit currents in generator-fed is reduced. Also, the damages due to faults in being out of service duration are reduced, that increases the availability of the power-plant [1]. In [1,12], the authors present a method based on the cut and path set theory to evaluate the influence of the generator breaker on the reliability of power plant layouts. Although the cut–set theory is a basic method for reliability evaluation, but this method is restricted especially when the number of elements is increased in under study test system. For
solving this problem, in this paper SMCS is used to reliability assessment. SMCS is a suitable tool to deal with large scale system [13]. Although the simulation time in SMCS is more than the analytically methods; but the reliability assessment is an off-line procedure and time is not an important factor [13–19].

This paper deals with reliability assessment in different types of power plant substation configurations. Karun III as one of the most important hydro power plants in ING is considered as case study. Regarding the importance of the reliability, one and half circuit breaker topology has been used in this substation. The main purposes of this study are to evaluate the effect of the other substation layouts such as two-breaker layout topology that simultaneously are equipped with generator breaker and bus-section. Different cases with and without presence of bus-section and generator breaker are investigated. The most commonly used reliability indices such as EENS, LOLE and ELC are used to evaluate the reliability. Economical evaluation of the different layouts is studied.

Apart from above introductory, this paper is arranged in following sections: In Section 2, different layout models are briefly introduced. Reliability evaluation with SMCS is presented in Section 3. Section 4 is devoted to the proposed method and system

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**Nomenclature**

- AC-OPF: alternative current optimal power flow
- AIS: air insulation substation
- EENS: expected energy not served
- EHV: extra high voltage
- ELC: expected load curtailment
- FOR: forced outage rate
- GIS: gas insulation substation
- ING: Iran national grid

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Fig. 1. (A) One and half-breaker system with bus-section set and generator breaker. (B) The general schematic of busbar layout in two-breaker system. D: disconnector; B: breaker; G: generator; L: line; T: transformer.
data are given in Section 5. Eventually the simulation results are provided in Section 6.

2. Different busbar layouts in substation

The basic structure of the busbar layouts in one and half and two-breaker power plants are depicted in Fig. 1. The Generator and transformer set are connected to the busbar layout through lines L11 and L12. The lines L21 and L22 are also external lines from busbar, which connect the power-plant to the main network. It should be noted that in ordinary condition, generator breakers and bus-sections are not available in all under study topologies. The breaker-and-a-half scheme is configured with a circuit between two-breakers in a three-breaker line-up with two buses. In many cases, this is the next development stage of a ring bus arrangement. The configuration of one and half-breaker busbar which is usually used in power-plant substations has high reliability and flexibility. In this layout, three breakers are used for two feeders that all breakers are normally closed. In this topology, even if one of the buses be failed, the transmission power will be provided without any interruption. This configuration provides suitable reliability; with proper operating relay protection and a single circuit failure will not interrupt any other circuits. Furthermore, a bus-section fault, unlike the ring bus layout, will not interrupt any circuit loads. The structure of two-breaker busbar layout, which is common in extra high voltage power-plant substations, has very high reliability and flexibility. In this system, four breakers are used for two feeders. Essentially, one and half and two-breaker systems are both expensive; however, two-breaker layout has higher expense with respect to one and half-breaker system. In two-breaker system, one of the breakers is often out of service. It worth mentioning that, purpose of this paper is to study and compare the most commonly used busbar layouts in extra high voltage power system. It should be noted that these two substation switching arrangement especially one and half breaker system are the most common arrangement in 230 and 400 kV substations in ING.

3. Reliability modeling by using sequential Monte Carlo simulation

In this paper, the reliability indices such as EENS, LOLE and ELC are simulated by using SMCS and the approach of alternative current optimal power flow (AC-OPF). In order to reliability evaluation, we should evaluate the reliability of each plan under a given scenario. At the first, the system data (such as generation capacity and the expected load level) are specified in each scenario. It is assumed that system load follows a normal distribution; where, the mean and variance of load are estimated from historical data. SMCS is then employed. In iterations of simulation, system load is randomly generated based on the estimated normal distribution. Then AC-OPF is calculated and the amount of unsupplied power is recorded. After iterations are finished, the EENS is calculated as the average amount of unsupplied power in the simulation process. Steps of SMCS approach for system reliability evaluation includes the following basic steps [13–19].

Step 1: In first, all states of system are selected. This includes a load level and states of all system components (up, down, or derated states).

Step 2: Power flow and contingency analysis for the selected system state is performed to check if there is a system problem (overloading, voltage limit violations, isolated buses, etc.).

Step 3: If there is no system problem; go back to Step 1 to select a new system state. Otherwise, go to Step 4.

Step 4: Remedial actions are performed. This is often an OPF model. The purpose of the model is to reschedule generations, alleviate line overloading or voltage limit violations, and avoid load curtailments if possible, or minimize the total load curtailments if unavoidable.

Step 5: Reliability indices based on results in Step 4 is updated.

Step 6: Steps 1–5 are repeated until a stopping criterion is met.

3.1. Calculation of the reliability indices

In this paper the reliability of system is evaluated by EENS, LOLE and ELC indices. EENS index is the expected amount of power that is not supplied and LOLE is loss of load expectation and ELC is expected load curtailment. These indices are calculated as follows:

\[
\text{EENS} = \frac{\sum_{j=1}^{N} \text{Total amount of load}}{N_S} \quad \text{(MW h/year)} (1)
\]

\[
\text{LOLE} = \frac{\sum_{j=1}^{N} \text{Total hours of loss of load}}{N_S} \quad \text{(hours/year)} (2)
\]

\[
\text{ELC} = \frac{\sum_{j=1}^{N} \text{Total loss of MW}}{N_S} \quad \text{(MW/year)} (3)
\]

In all equation \(N_S\) is the under study time period that is a year for this study. The OPF associated with scenario-based SMCS is used to calculate the proposed indices. In each scenario of the SMCS, a random number is generated for each component such as line, generator, and breaker. Then, the components which their random number is lesser than their failure rate are considered as uninstalled in that scenario. Then, the AC-OPF is performed to determine the unsupplied power. The EENS is evaluated as the average of unsupplied powers related to all scenarios.

4. The proposed methodology

In this paper SMCS is used to calculate the reliability indices. Fig. 2 shows the proposed method in details. In first in block A, a random number is generated for each component. Then in block B, the components which their related random numbers is lesser than FOR are considered as uninstalled. In block C, the AC-OPF is performed and unsupplied powers are calculated in block D. Also, the repair time for the unsupplied components is calculated in block E. this process is repeated to converge. After convergence, the reliability indices are calculated by using Eqs. (1)–(3). The AC-OPF is completely presented in [20]. In this paper, the AC-OPF is carried out by using power system analyzer toolbox [20].

4.1. Economic evaluation of the busbar layouts

In order to economical evaluation, two costs are considered as follows:

i. Investment cost of layout such as cost of breakers and disconnector.

ii. Cost of unsupplied powers.

The unit of investment cost of layout is per “USA dollar” and unsupplied power is in “kW h/year”. In order to comparison, these two costs are converted to “$/year” which is annual cost. Annual investment cost is calculated as follows [1]:

\[
A_C = C \left[ \frac{i(1+i)^n}{(1+i)^n-1} \right] (4)
\]
In this equation, \( C \) is the total initial cost of the project (consist of initial cost, installation, reparations and maintenance), \( A_C \) is the annual cost; \( i \) stands for annual rate of growth of money, and \( n \) for the life-span of the project (per years). It should be noted that the effective factors in annually benefits are: the changes in system failure rate, the changes in time duration of equipments repairing, the maximum value of annually energy transferring from related layout, and the cost of each kW h energy. Also, the annual cost of unsupplied power is calculated as follows:

\[
\text{Annual cost of unsupplied power (\\$/year)} = \frac{EENS (MW h/year) \times \text{Cost of energy (\\$/MW h)}}{5}
\]  

(5)

Thus, the total cost of a layout is calculated as sum of these two costs. It should be noted that in practice, the life time cost of system consists of acquisition costs, civil work costs, installation costs, maintenance costs and ground costs. But, in this study the installation and maintenance costs are considered and the others are neglected.

5. Under study system data

Karun III hydro power station contains 8 units that each one generates 250 MW in nominal condition. In this study, each of considered system layouts has two bays in which there is a 250 MW generator with terminal voltage 15.75 kV and a 15.75/400 kV and 300 MVA transformer. The initial investing costs of the system elements, life cycle of the plan, and the annual growth rate of the money are provided in Table 1. The Reliability values of the elements are presented in Table 2 [21–24].

Regarding the importance of the generators breakers, in this section, the effect of this breaker is analyzed. The reason of this importance is that, the generator breaker can significantly prevent from the possible dangers, especially explosion, in the generator transformers. It should be noted that the repairing of the main transformer in the case that the failure is not due to the explosion in the tank takes almost 1 month time and in the case of the tank explosion, it may take one year time. Therefore, using the generator breaker leads to reducing the MTTR and also failure rate [1]. It should be noted that generator reliability indices are improved as shown in Table 2, when generator breaker is used. Also generator breaker has less failure rate than other breakers; however its repair time is more than conventional breakers. Five cases are considered for simulation. Table 3 shows the related components to each case. These cases are as follows:

Case 1: System without bus-section and generator breaker.
Case 2: System with only disconnector as a bus-section and without generator breaker.

Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Life cycle of plan (n)</td>
<td>30 years</td>
</tr>
<tr>
<td>Annual growth rate of money (i)</td>
<td>10%</td>
</tr>
<tr>
<td>Approximated cost of 400 kV breaker</td>
<td>165,000 $</td>
</tr>
<tr>
<td>Approximated cost of the generator breaker</td>
<td>220,000 $</td>
</tr>
<tr>
<td>Approximated cost of 400 kV disconnector</td>
<td>45,000 $</td>
</tr>
<tr>
<td>Approximated cost of 1 kW h energy</td>
<td>0.06 $</td>
</tr>
</tbody>
</table>

Fig. 2. The proposed method flowchart.

Table 2

<table>
<thead>
<tr>
<th>Parameters elements</th>
<th>( x_i ) (Failure per year)</th>
<th>( U_i ) (Hour per year)</th>
<th>( r_i ) (Hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1–G2</td>
<td>0.08</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>G1(^{a})–G2(^{a})</td>
<td>0.065</td>
<td>8</td>
<td>80</td>
</tr>
<tr>
<td>T1–T2</td>
<td>0.0153</td>
<td>5.50</td>
<td>192</td>
</tr>
<tr>
<td>L11–L12–L21–L22</td>
<td>0.01437</td>
<td>0.296</td>
<td>4.3</td>
</tr>
<tr>
<td>Breakers B1 ... B8</td>
<td>0.015</td>
<td>1</td>
<td>70</td>
</tr>
<tr>
<td>Breakers B9, B10</td>
<td>0.008</td>
<td>0.8</td>
<td>110</td>
</tr>
<tr>
<td>Buses 1 and 2</td>
<td>0.01437</td>
<td>0.001</td>
<td>9.5</td>
</tr>
<tr>
<td>Disconnects D1 ... D10</td>
<td>0.010</td>
<td>0.02</td>
<td>4.0</td>
</tr>
</tbody>
</table>

\(^{a}\) The improved values of generator reliability indices when generator breaker is used.

Table 3

<table>
<thead>
<tr>
<th>Disconnector in buses 1 and 2 as a bus-section</th>
<th>The set of Breaker and disconnector in buses 1 and 2 as a bus-section</th>
<th>Generator breaker in each generator terminal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Case 2</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Case 3</td>
<td>–</td>
<td>✓</td>
</tr>
<tr>
<td>Case 4</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Case 5</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Fig. 2. The proposed method flowchart.
Case 3: System with the set of breaker and disconnector as a bus-section and without generator breaker.
Case 4: System with the set of breaker and disconnector as a bus-section and generator breaker.
Case 5: System with only generator breaker.

6. Simulation results

The simulation results of the proposed method which has been accomplished by MATLAB software are presented in this section. SMCS is sampled to convergence for each case. The simulation results of all cases for one and half-breaker system are provided in Table 4. As an example, the SMCS iterations and convergence performance for 1.5 breaker case 3 is depicted in Fig. 3.

It is clearly seen that, with increasing iterations, the output is converged. Table 4 shows that, with increasing power system components, the reliability index LOLE is growing up. But, the reliability index EENS depends to the system topology. Also, the simulation results of all cases for two-breaker system are provided in Table 5. In this state, such as the former one, with increasing the components of system, the reliability index LOLE is increased.

The effect of two components should be discussed in more details: bus-section and generator breaker. Bus-section can sectionalize a bus to two sections. In this situation, one section can be out of service, while the other section is in service. Thus, bus-section affects on the system reliability and reduces the EENS. Also the existence of bus-section, reduces the repair time significantly, however failure rate of the system is increased. In case 4 which the generator breaker is added to the system, the reliability index EENS is significantly reduced. It should be noted that simultaneous using of the generator breaker and bus-section set in this case not only improve the reliability indices of the system, but also reduce the system repair time significantly. Simulation results in Tables 4 and 5 show that using only the generator breaker in case 5 leads to improve the ELC, LOLE and EENS of the layouts in both one and half and two-breaker system. This issue shows the importance of generator breaker. Hence, generator breaker is a key component in power system reliability and protection.

6.1. Comparison of the results for two busbar layouts

The presented busbar topologies in this paper (one and half-breaker and two-breaker system) are the most commonly used layouts in the power system. Thus, comparison of these layouts from view of reliability and also economic is favorable. As shown in Tables 4 and 5, it is clear that the two-breaker system is more reliable than one and half-breaker system. But in this topology 8 breakers are used, while, in the one and half-breaker system 6 breakers are installed. Therefore, two-breaker system has a more investing cost. Fig. 4 shows the reliability index EENS for two systems. It is clearly seen that, in all cases, the two-breaker system is more reliable.

Comparison of two test cases in economical point of view is presented in Table 6. It is seen that in all cases, the investment cost of two-breaker system is more than the other system, but its unsupplied power cost is lower. Eventually, the total cost of one and half breaker is lower than the two-breaker in all cases. Fig. 5 shows the comparison of total cost for two test systems. It is seen that one and half breaker system has lower cost than two-breaker system in all cases. Thus, one and half breaker system is a better choice for installation in economical point of view.

6.2. Study the effect of components outage

As referred before, generator breaker is an important component in power system. The other components such as generator are very important components too. Thus, it is suitable to study the effect of this component on the reliability indices. For this matter, the effect of generator FOR and generator breaker FOR are evaluated on the reliability indices for both one and half and two-breaker layouts. Figs. 6–9 show the reliability indices versus generator and generator breaker FOR variation. Fig. 6 shows the changes of EENS index versus FOR variation of generator.

With increasing FOR, the EENS is increased, but the changes are not linear. Decreasing the FOR of generators is very discussing issues in power systems. A generator with lower FOR is more reliable

<table>
<thead>
<tr>
<th>Case</th>
<th>ELC (MW/year)</th>
<th>LOLE (h/year)</th>
<th>EENS (MW h/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>28.1180</td>
<td>17.9592</td>
<td>504.9757</td>
</tr>
<tr>
<td>Case 2</td>
<td>24.8383</td>
<td>17.1079</td>
<td>424.9303</td>
</tr>
<tr>
<td>Case 3</td>
<td>33.0219</td>
<td>19.2212</td>
<td>634.7228</td>
</tr>
<tr>
<td>Case 4</td>
<td>25.1364</td>
<td>16.1525</td>
<td>406.0166</td>
</tr>
<tr>
<td>Case 5</td>
<td>20.9826</td>
<td>12.3772</td>
<td>259.7058</td>
</tr>
</tbody>
</table>

Table 5

The reliability indices for two-breaker system.

<table>
<thead>
<tr>
<th>Case</th>
<th>ELC (MW/year)</th>
<th>LOLE (h/year)</th>
<th>EENS (MW h/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>17.5524</td>
<td>18.4629</td>
<td>324.0674</td>
</tr>
<tr>
<td>Case 2</td>
<td>15.4360</td>
<td>18.8521</td>
<td>291.001</td>
</tr>
<tr>
<td>Case 3</td>
<td>18.3537</td>
<td>19.4338</td>
<td>356.6818</td>
</tr>
<tr>
<td>Case 4</td>
<td>13.1359</td>
<td>17.7647</td>
<td>233.3557</td>
</tr>
<tr>
<td>Case 5</td>
<td>12.5373</td>
<td>16.1857</td>
<td>215.5906</td>
</tr>
</tbody>
</table>

Fig. 3. Monte Carlo iterations convergence for one and half breaker (case 3).

Fig. 4. Comparison of EENS index for two test cases.
and also more expensive. Thus, it is necessary to trade-off between reliability and cost. Fig. 6 shows that decreasing FOR lower 0.06 does not have a significantly effect on the reliability. So it is not necessary to make an expensive generator with FOR lesser than 0.06. Also, Fig. 7 shows the LOLE index versus FOR of generator. The LOLE is increased along with increasing the FOR.

The effect of generator breaker FOR is investigated in Figs. 8 and 9. It can be seen that with increasing the generator breaker FOR, the EENS and LOLE are increased. A generator breaker with lower FOR is more reliable and also more expensive. Thus, again it is necessary to trade-off between reliability and cost.

### Table 6
Economical comparison of two test cases. System 1: One and half breaker system. System 2: Two-breaker system.

<table>
<thead>
<tr>
<th>Case</th>
<th>System 1</th>
<th>System 2</th>
<th>System 1</th>
<th>System 2</th>
<th>System 1</th>
<th>System 2</th>
<th>System 1</th>
<th>System 2</th>
<th>System 1</th>
<th>System 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.53</td>
<td>2.04</td>
<td>1.62</td>
<td>2.13</td>
<td>2.04</td>
<td>2.55</td>
<td>2.48</td>
<td>2.99</td>
<td>1.97</td>
<td>2.48</td>
</tr>
<tr>
<td>2</td>
<td>0.16230</td>
<td>0.21640</td>
<td>0.17185</td>
<td>0.22595</td>
<td>0.21640</td>
<td>0.27050</td>
<td>0.26308</td>
<td>0.31718</td>
<td>0.20898</td>
<td>0.26308</td>
</tr>
<tr>
<td>3</td>
<td>0.03029</td>
<td>0.01944</td>
<td>0.02549</td>
<td>0.01746</td>
<td>0.03808</td>
<td>0.02140</td>
<td>0.02436</td>
<td>0.01400</td>
<td>0.01558</td>
<td>0.01293</td>
</tr>
<tr>
<td>4</td>
<td>0.1926</td>
<td>0.23585</td>
<td>0.19734</td>
<td>0.24341</td>
<td>0.25449</td>
<td>0.29190</td>
<td>0.28744</td>
<td>0.33118</td>
<td>0.15582</td>
<td>0.27601</td>
</tr>
<tr>
<td>5</td>
<td>0.03029</td>
<td>0.01944</td>
<td>0.02549</td>
<td>0.01746</td>
<td>0.03808</td>
<td>0.02140</td>
<td>0.02436</td>
<td>0.01400</td>
<td>0.01558</td>
<td>0.01293</td>
</tr>
</tbody>
</table>

![Fig. 5. Comparison of total cost for two test cases.](image)

![Fig. 6. EENS versus FOR variation of generators.](image)

![Fig. 7. LOLE versus FOR variation of generators.](image)

![Fig. 8. EENS versus FOR variation of generators breaker.](image)

![Fig. 9. LOLE versus FOR variation of generators breaker.](image)
Fig. 8 shows that decreasing FOR lower 0.008 does not have a significantly effect on the reliability. So it is not necessary to make an expensive generator breaker with FOR lesser than 0.008. Also Figs. 6 and 8 show that EENS of one and half breaker system more sensitive than two-breaker system in case of FOR variation of generator and generator breaker.

7. Conclusion

In this paper reliability of two commonly used busbar layouts was compared. Due to widely usage of these topologies in power system, the paper results are suitable for real world applications. The proposed comparison was carried out from view of investment cost and unsupplied power cost. Simulation results showed that two-breaker layout is more reliable and also needs more investment cost; but, one and half breaker system needs lesser investment cost and leads to more unsupplied power. Considering total cost, the one and half breaker layout is more economical than the other topology. Simulation results show that how we can provide a trade-off between reliability and cost with regard to the FOR variation of components. With regard to the importance of reliability assessment in power systems, following issues are suggested as further work in this field:

(a) Reliability assessment with consideration of uncertainty in generation system.
(b) Reliability assessment from view of private generation companies which aim at maximizing profit instead of minimizing cost.
(c) Considering aging in components.
(d) Evaluation of reactive power effects on the reliability.

References