

Supplementary

Graphical Ways to Visualize Operational Risk Results for Transmission System Contingencies

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1. Introduction

This document is an extended version of the main paper that represent the operational risk result visualization from the heat-map and the risk-based contingency chart under different operating conditions for specified operational risk indices. Through which the grid operator can characterize each individual contingency case from the probability and impact aspect. As mentioned in the main paper that for probabilistic contingency analysis four types of technical operational risks have been considered. And in every four types of operation risk, different operating conditions are created by varying the generation loading level of the grid and perform probabilistic contingency analysis in each operating condition.

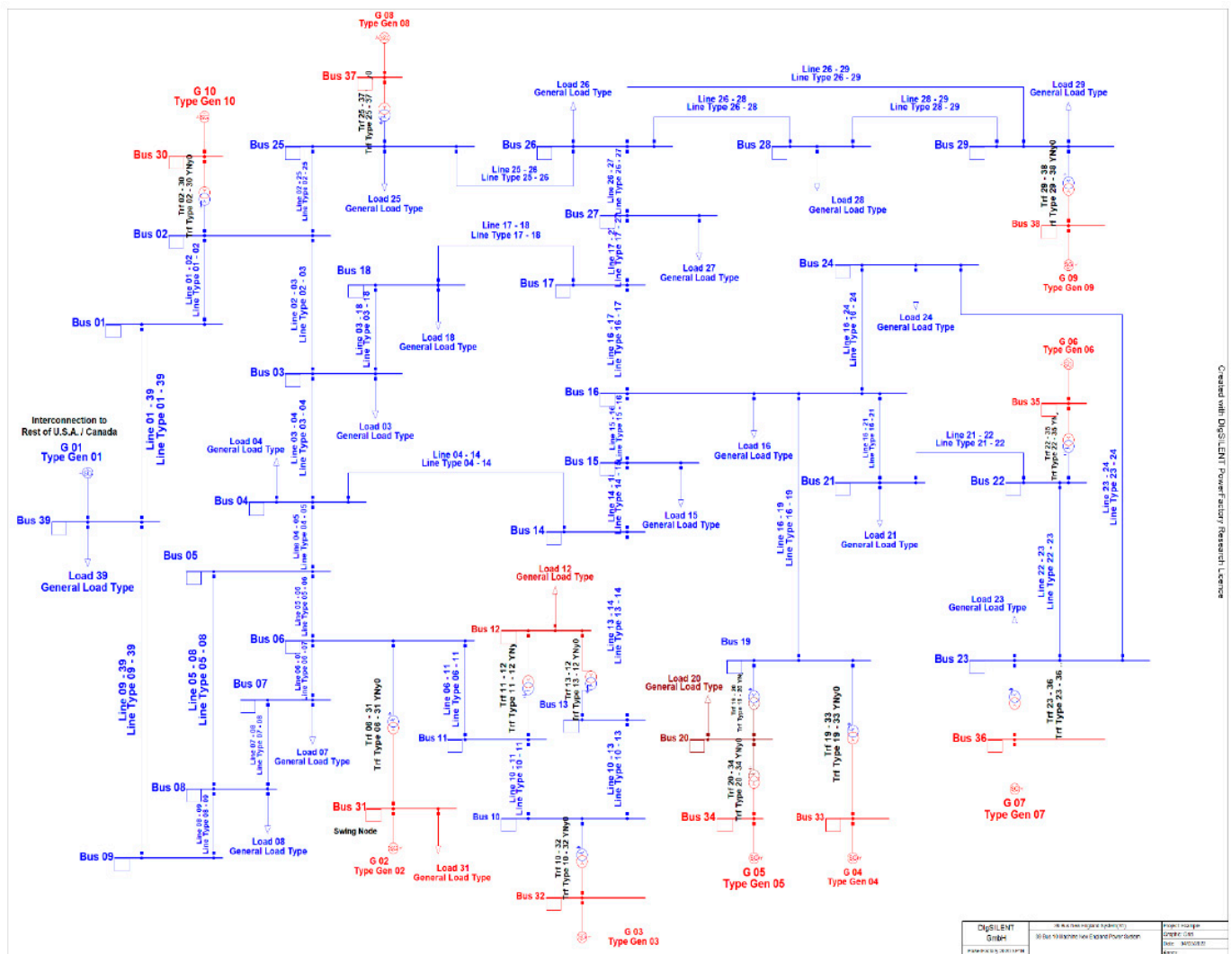


Figure S1. New England IEEE 39-BusTest system.

As mentioned in the article and earlier that four different “post contingency network studies” are done to analyses the probabilistic contingency behaviour, extreme loading, over-voltage, undervoltage and system collapse. For this purpose, “New England IEEE 39 Bus Test system” is selected, because it is a simplified model of a high voltage transmission system. The main voltage level of this selected grid is 345 kV. As depicted in Figure S1 it consists of 10 generators, 34 transmission- Lines, 19 load points, and 12 transformers. For contingency definition transmission Lines, transformers, and generators are considered. Overvoltage and undervoltage post contingency impact is quantified on various bus bars, instead, the extreme loading post contingency impact is quantified in transmission lines and transformers. System collapse post contingency studies are done through non-convergence contingency cases. In addition, different operating conditions are created by varying the generation and loading levels under maintaining the balance between generation and consumption. This was just a brief explanation about the selected grid, and now the contingency pattern under (40%, 60% and 80%) increment in generation loading level is discussed in detail in Section 2.

2. Contingency Patterns in Operational Risk under Different Operating Conditions

2.1 Contingency Pattern in Operational Risk of Extreme Loading

2.1.1 2nd Operational Condition (40% Increment Generation Loading Mix)

To create 2nd operational scenario/condition in the same grid, generation level and loading demand is incremented evenly, and perform contingency analysis to visualize that whether the number of contingencies and their impact is increasing or decreasing. In this operational condition i.e., (40% increment in standard GLM), contingency number 1121 (27, 43) in which Line 21–22 and generator G–09 outage is involved are taking maximum contribution. In actual it is creating high loading continuous (L.C) value on many components for instance: it creates (265.2 L.C) across Line 23–24, (176.3 L.C) across Line 22–23 which is attached between Bus 22 and 23, (175.1 L.C) across Line 16–24, (172.9 L.C) across Line 16–19, (144.2 L.C) across Line 25–26, (138.3 L.C) across Trf (19–33), transformer attached between Bus 19 to Bus 33, (133.9 L.C) across Trf (22–35), (129.5 L.C) across Trf (25–37), (128.4 L.C) across Trf (23–36), and 86.9 Line 26–28. Accumulatively the severity of this (N-2) contingent event would be the (1550.7 L.C) The probability of occurrence of this contingency event (i.e. 0.4137) is also high. Correspondingly the contribution of this contingency to the extreme loading risk is (641.52 L.C) depicted in Figure S2.

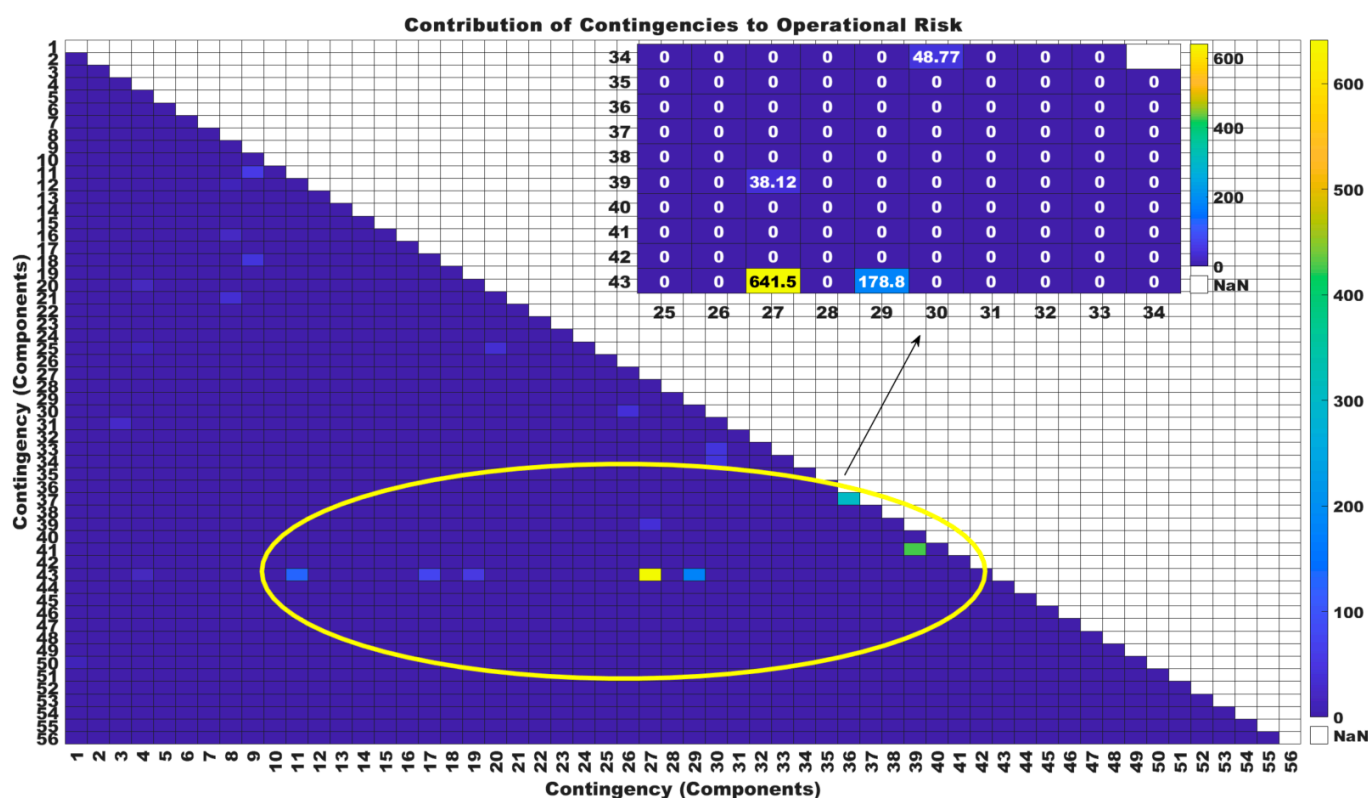


Figure S2. Contribution of extreme-loading contingencies at 40%-GLM.

2.1.2. 3rd Operational Condition (60% Increment in GLM)

To create a 3rd operational scenario generation loading level is increased up to 60% by maintaining the balance between generations and loading demand. Figure S3 depicting the contingency behaviour under the 3rd operational scenario in which the contingency number (1437) i.e. (42, 44) shows the maximum contribution (383 L.C) towards the operational risk of extreme-loading. The probability of occurrence of this contingency is 0.6195 and the impact of this contingency is 618.2, correspondingly the risk of overloading due to this contingency would be (383 L.C). The contingency (1437, in which G08–G10 is involved) creates maximum loading continuous value; (428.5 L.C) across Trf (06–31) and (189.7 L.C) across Trf (10–32). While after doing network studies, contingency number (133), i.e., (3, 27) in which (Line 02–03) that attached between Bus 02 and Bus 03 and-Line 21–22) attached between Bus 21 and Bus 22 is involved depicting the highest impact (1057 L.C). It creates 318 L.C across (Line 23–24), 214 L.C across (Line 16–24), (210.3 L.C) across (Line 22–23), 160.0 L.C across (Trf 22–35) and (154.0 L.C.) across Trf (23–36). So in contri-

bution to the overall risk, both the probability of occurrence and the impact of the contingency event are important. Here specified contingency, their impact, effecting components, and their probability of occurrence are analysing, but in the control room, TSO can analyse all the contingency and take preventive measures within the lead-time.

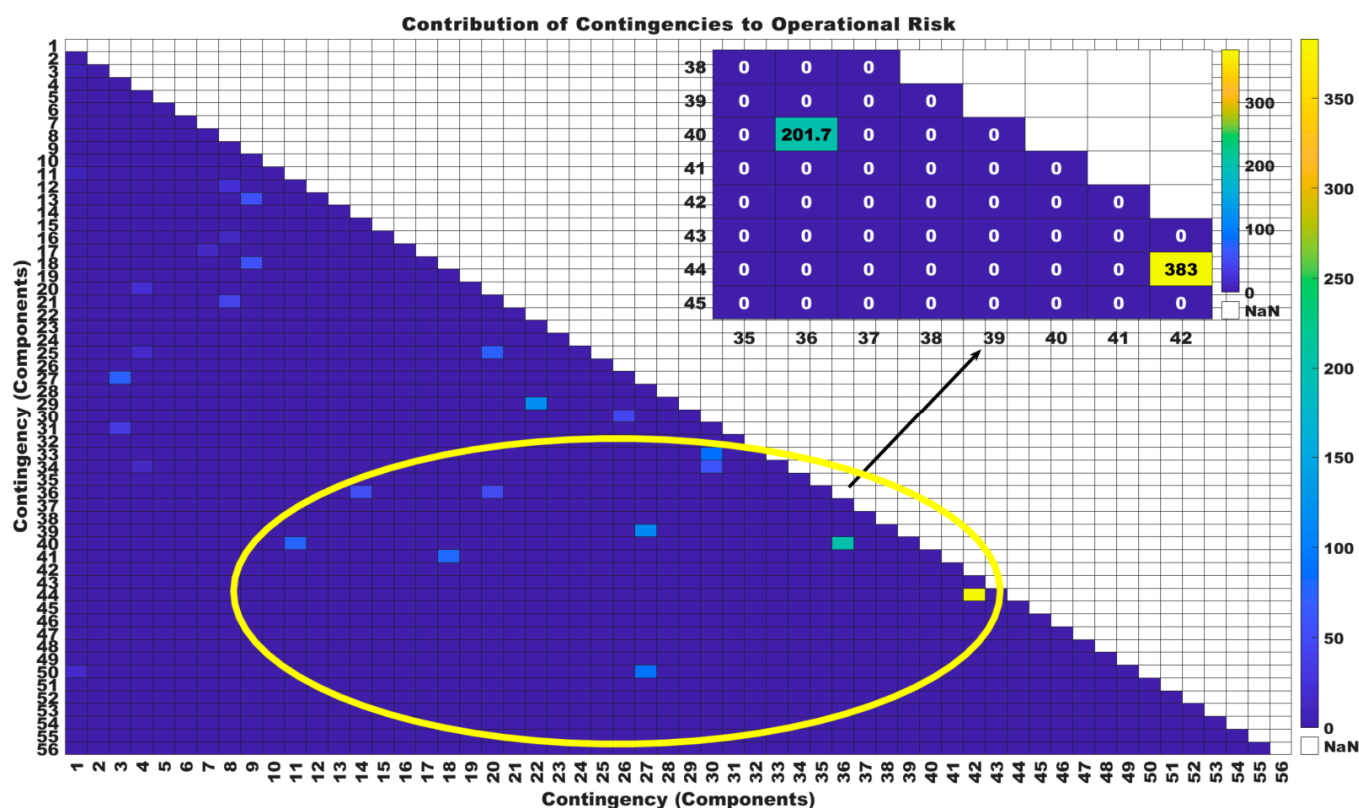


Figure S3. Contribution of extreme-loading contingencies at 60%-GLM.

2.1.3. 4th Operational Condition (80% Increment in GLM)

For the 4th operational condition, the generation loading mix increases up to 80% to quantify the grid operational security under worst scenarios. In this case, contingency number 1377 in which (G04–Trf 06–31) is involved has more contribution towards the operational risk of extreme loading. For instance when contingency 1377 occurred this creating a loading continuous value across many components. For instance; it creates (290.6L.C) across Line (02–03), (258.9 L.C), across Line (08–09), (258.3L.C) across Line (09–39), (155.0L.C) across Trf (25–37), (91.2 L.C) across Trf (02–30). So accumulatively the impact of this contingency is (1054L.C). The probability of occurrence of this contingency is 0.5900 which is also high. That's why this contingency is taking maximum contribution to the risk of extreme loading i.e., 621.86 depicted in Figure S4 While the other contingency (136 in which component number 3 and 30 i.e. (Line 02–03 and Line 25–26) failure is involved, this has more impact as compared to contingency 1377 and impacts on many components through-loading continuous values. But due to the low probability of occurrence this contingency (136), has less contribution. From the above discussion of contingency pattern in each operating condition, it can be noticed that the highest contributing contingency and the effecting component is changing in every condition.

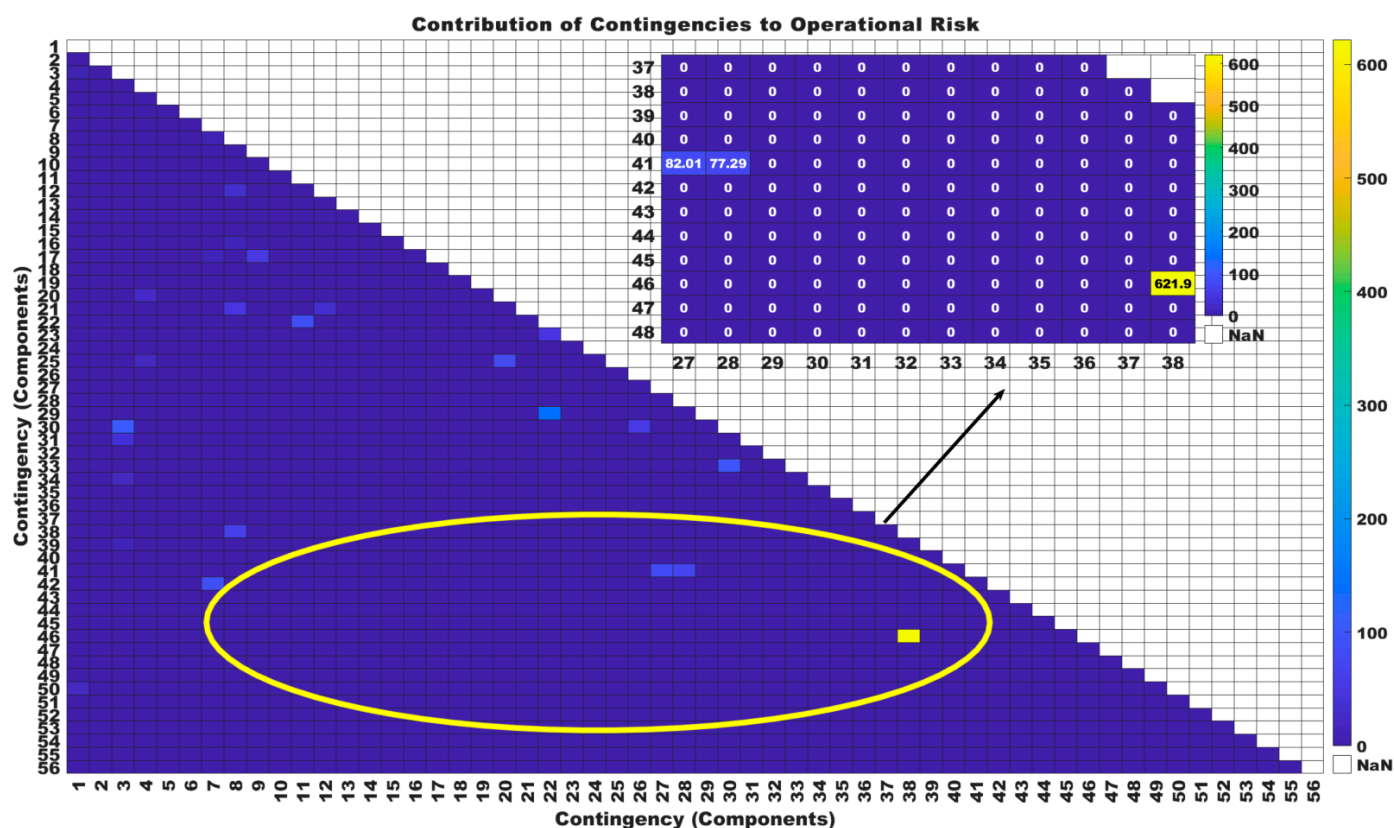


Figure S4. Contribution of extreme-loading contingencies at 80%-GLM.

2.2. Risk-based Contingency Charts

Risk-based Contingency Chart for Operational Risk of Extreme Loading

A risk-based contingency chart analyses the contingency event from the probability of occurrence and impacts aspect. In 2nd operating condition (Figure S5) mainly HIMP, MIHP contingency events are present. In 3rd operational scenario where the generation loading level increased up to the 60%, (Figure S6) mainly HILP (high impact low probability) and LIHP (low impact high probability) contingency event can be noticed and in 4th operational condition (Figure S7) mainly LIMP (Low impact medium probability), HILP (high impact low probability), and HILP (high impact low probability) contingent event can be noticed. It is not a compulsion that only these types of contingency event would be observed. Here in these figures trending contingency categories are involved. Consequentially “Risk-based contingency chart” helps to see the appearing contingency trends in a specified operating condition from probabilistic behaviour and impact.

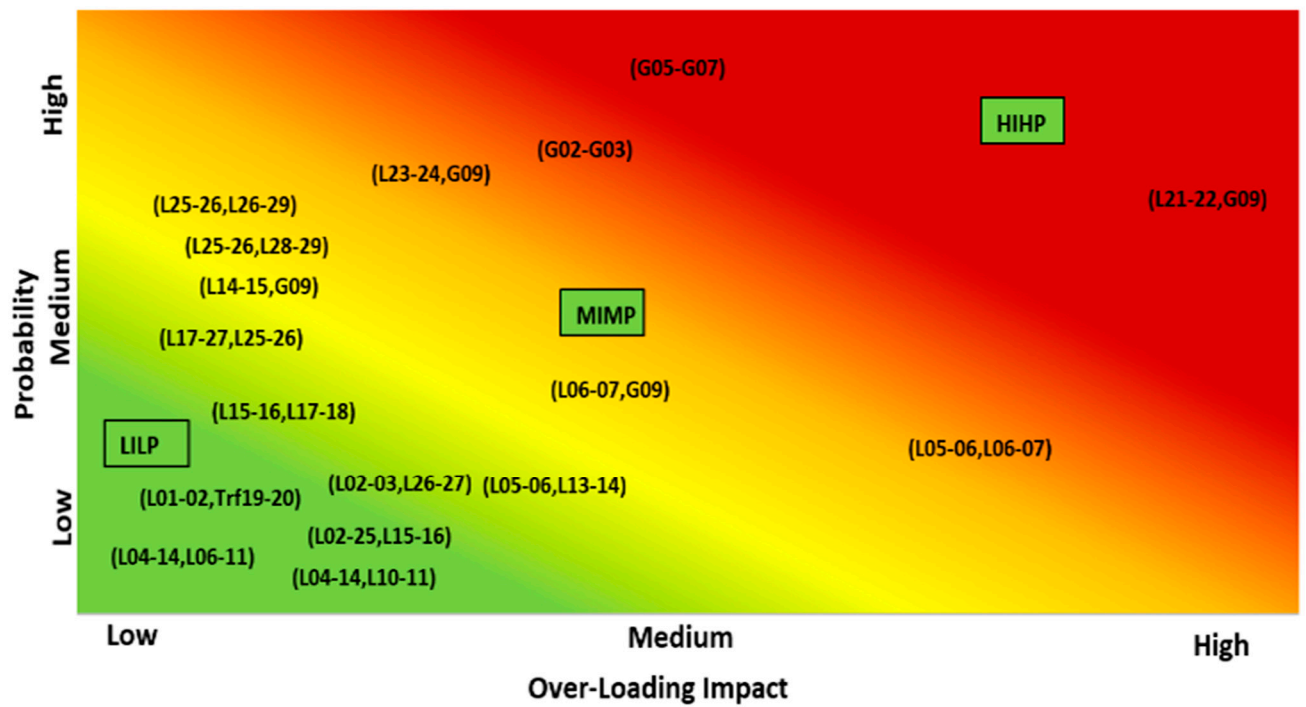


Figure S5. Extreme-loading Risk-based contingency chart under 2nd operating condition.

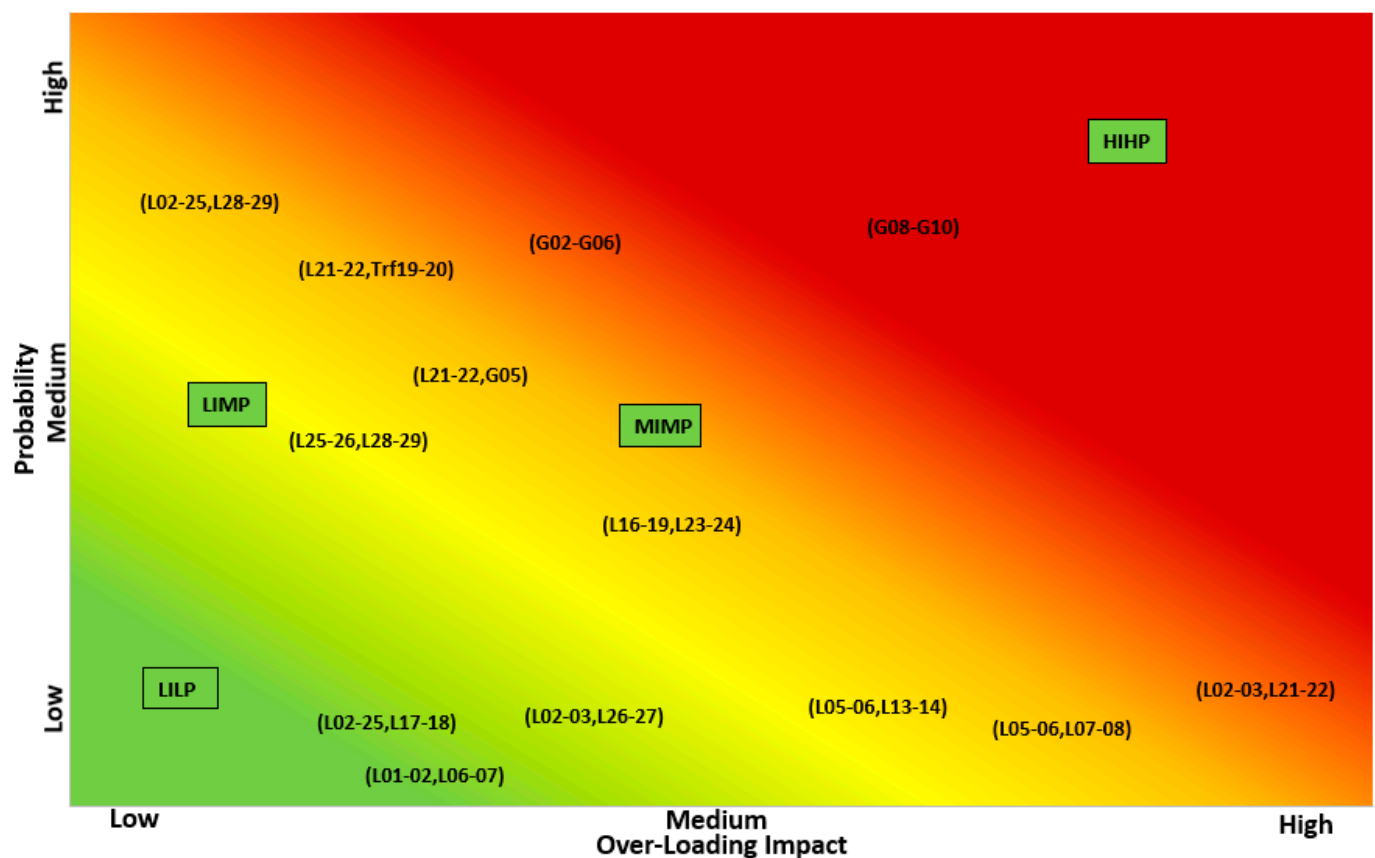


Figure S6. Extreme-loading Risk-based contingency chart under 3rd operating condition.

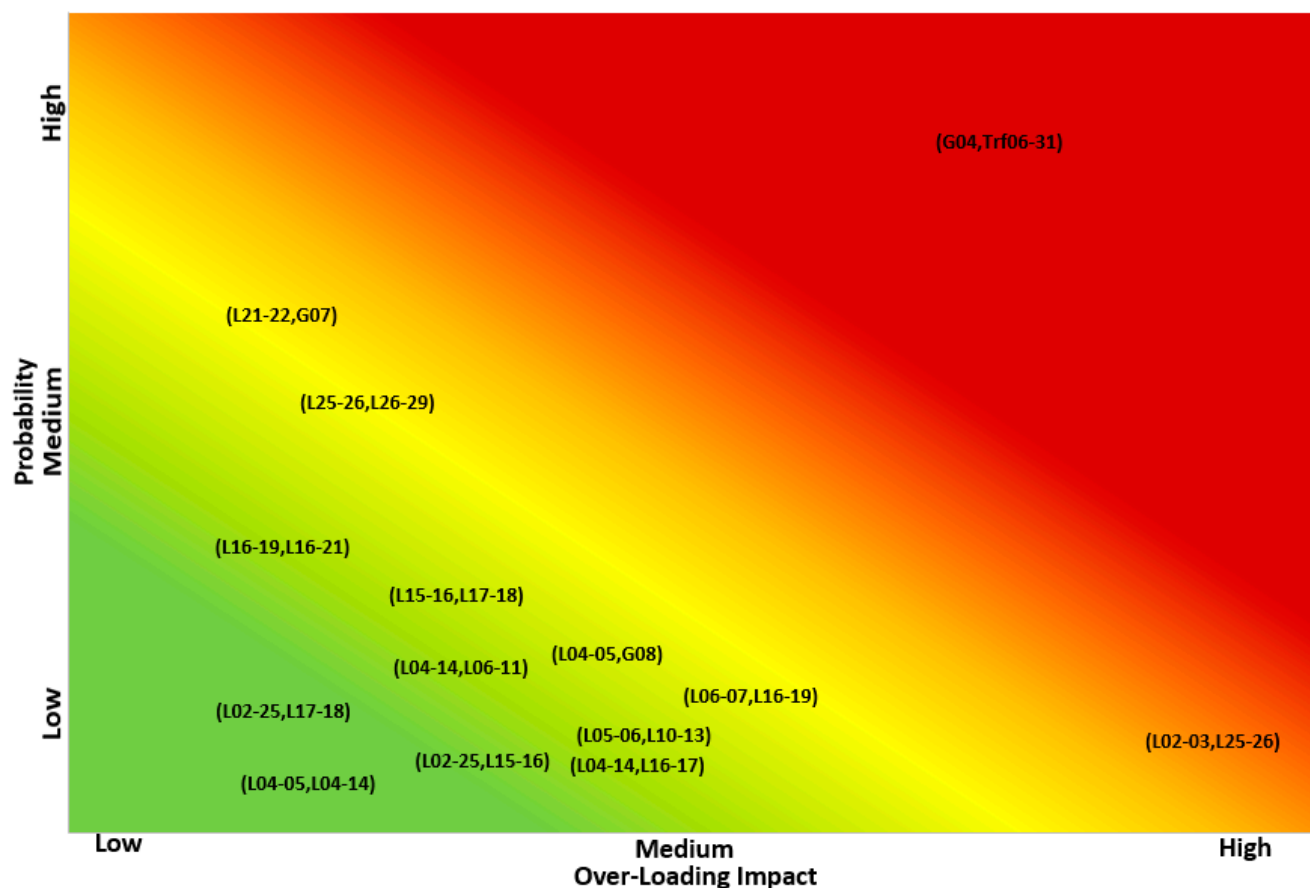


Figure S7. Extreme-loading Risk-based contingency chart under 4th operating condition.

3. Contingency Pattern in Operational Risk of Overvoltage

Contingency pattern in case of overvoltage under standard operating conditions has been discussed in the main paper, instead, here contingency behaviour under other different operating conditions is discussed.

3.1. Contingency Pattern Visualization through Heat-Map

3.1.1 2nd Operational Condition (40% Increment in GLM)

In the second operational scenario, when the generation loading mix is increased up to 40%, fewer contingencies but with high impact are contributing to the operational risk of overvoltage depicted in Figure S8. Mostly component numbers 24 (Line 16–24 i.e. Line attached between Bus 16–24), 22 (i.e., Line 16–19), and 31 (Line 26–27) are involved that could endanger the operational security of overvoltage. In this case, the most impact-full contingency is (24–27) in which Line (16–24) and Line (21–22) are involved and create an overvoltage of 1.078 p.u. at Bus–24, 1.066 p.u. at Bus–22, 1.064 p.u. at Bus–36, and 1.060 p.u. at Bus–23 respectively instead the threshold of overvoltage is set up to the 1.05 p.u. Bus 24; 22; 23 experience less impact of this contingency as compared to the standard operational scenario. The probability of occurrence of this contingency is 0.2503. So, consequently, in this operational condition, the contribution of this contingency would be high

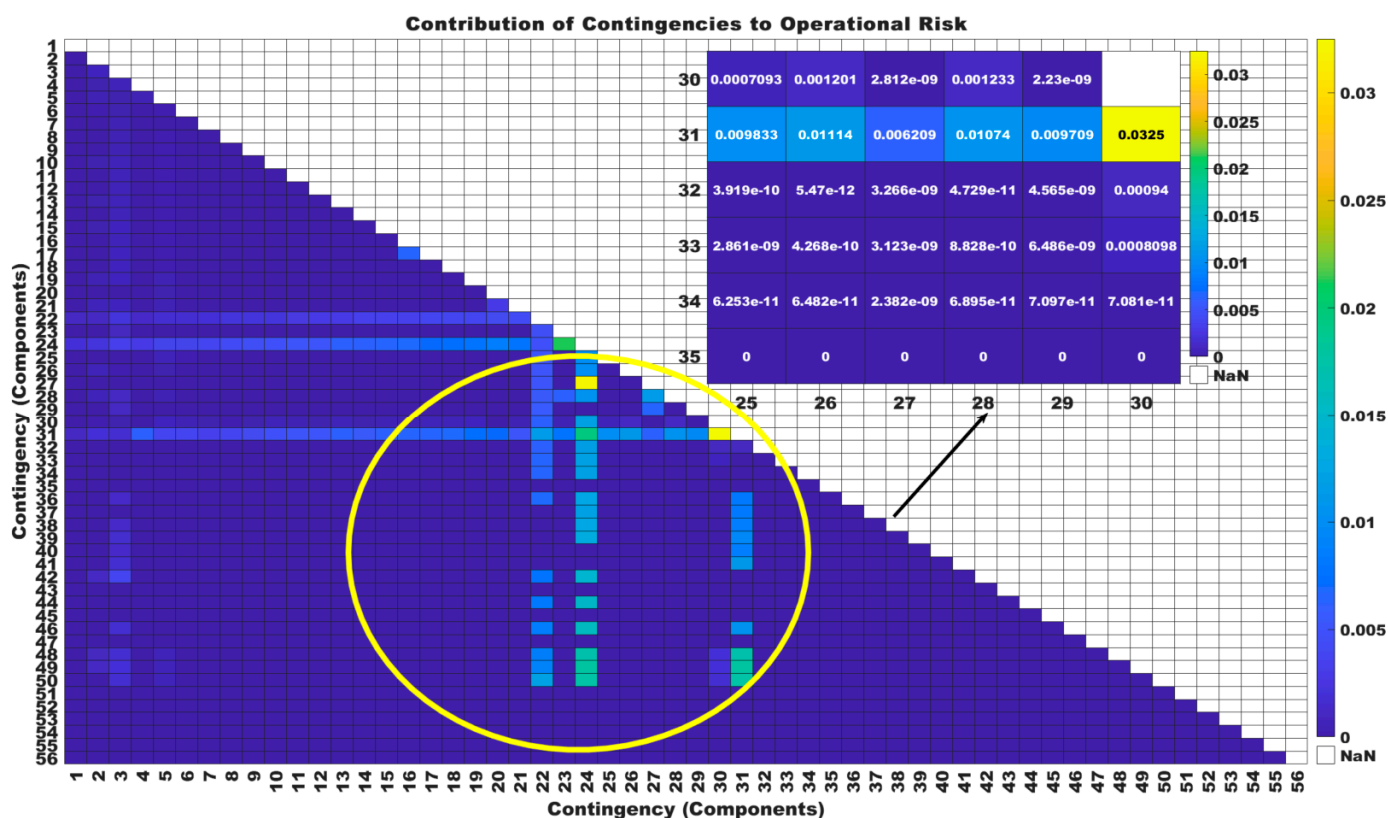


Figure S8. Contribution of over-voltage contingencies at 40%-GLM.

3.1.2. 3rd Operational Condition (60% Increment in GLM)

In the third operational scenario at which the generation and loading-level increases up to 60%. The number of contingencies and the impact of these should increase, but abnormality can be observed (Figure S9), the number of contingencies is decreasing. Yet, the highest contributing overvoltage contingencies and the probability of occurrence of both contingency 1015: (Line 16–24) the Line attached between Bus 16 to 24, (Line 21–22) attached between Bus 21 to 22 and contingency number 1190 in which (Line 25–26) attached between Bus 25 to 26, (Line 26–27) attached between are the same as with the previous operational scenario but the impact of these contingencies are high as compared to the 2nd operational condition. Now the contingency Line 16–24, Line 21–22 has an impact in terms of voltage-step of 0.1462 p.u. while the contingency 1190 has an impact of 0.1121 p.u. which creates an overvoltage of 1.067 p.u. at Bus:26, 1.064 p.u. at Bus:36, and of 1.053 p.u. at Bus:28.

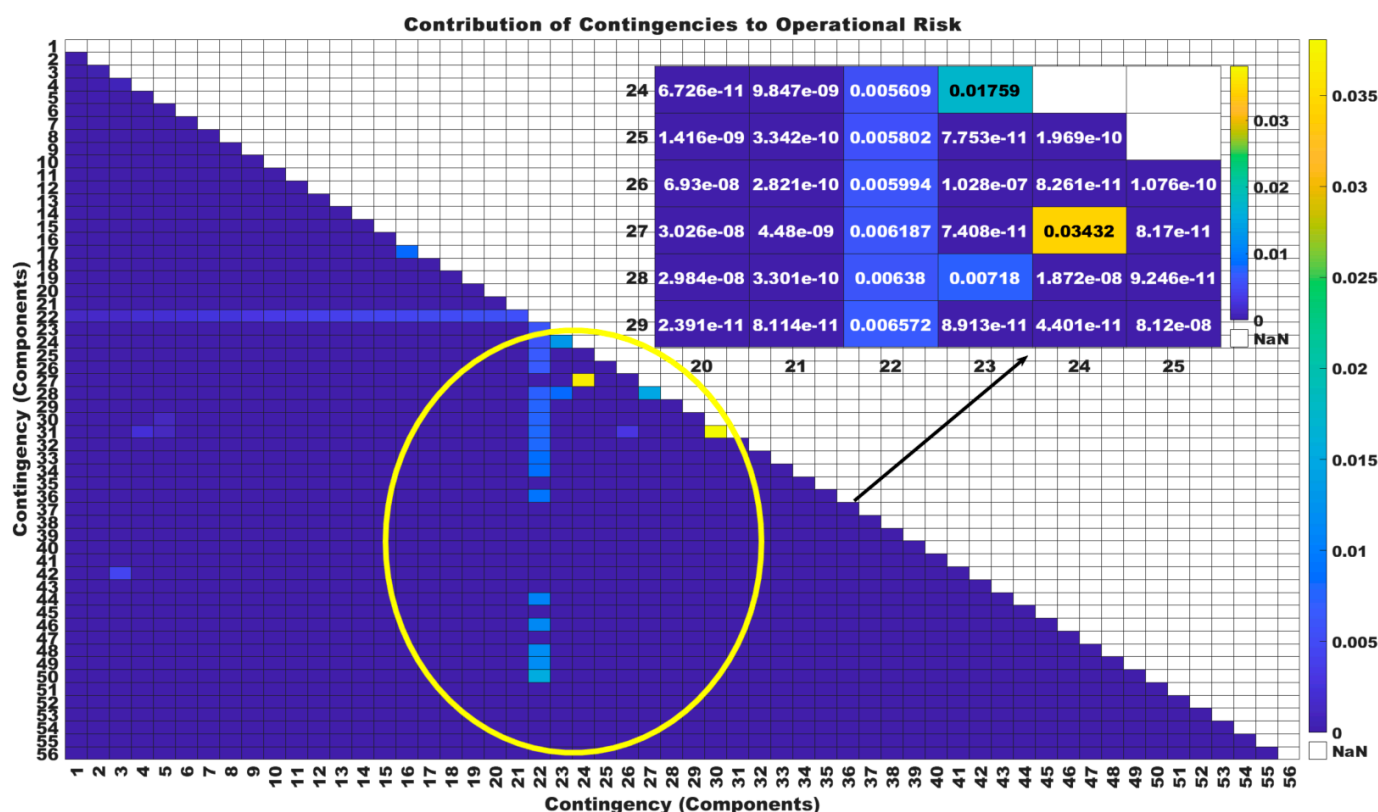


Figure S9. Contribution of over-voltage contingencies at 60%-GLM.

3.1.3. 4th Operational Condition (80% Increment in GLM)

As discussed earlier that contingencies cases should increase under peak operational conditions or maximum generation loading mix, however here abnormality can be seen due to the less number of contingencies depicted in Figure S10, the technical reason could be due to that the more number of contingencies are contributing towards the operational risk of system collapse due to crossing the defined threshold of overvoltage. In most appearing contingency component number 22 is involved. For instance (22, 46), (22, 48), (22, 49), (22, 50) shown in Figure S10. All these have a high probability of occurrence but less impact, even lesser than the 0.0566 p.u. As mentioned in the main paper the overvoltage contingency impact is quantified in terms of voltage step that consider the difference between the overvoltage and the base voltages. For instance, contingency number 969 (22, 49);, in which (Line 16–19) and Transformer (06–31) i.e. the transformer attached between Bus 06 and Bus 31, is involved. This contingency has a 0.37 probability of occurrence while it creating a voltage difference of 0.0390 at various buses. By doing overvoltage network studies, mostly Bus number 19 and Bus number 36 attached in IEEE-39 Bus network (refer to Figure S1) are affected and facing overvoltage.

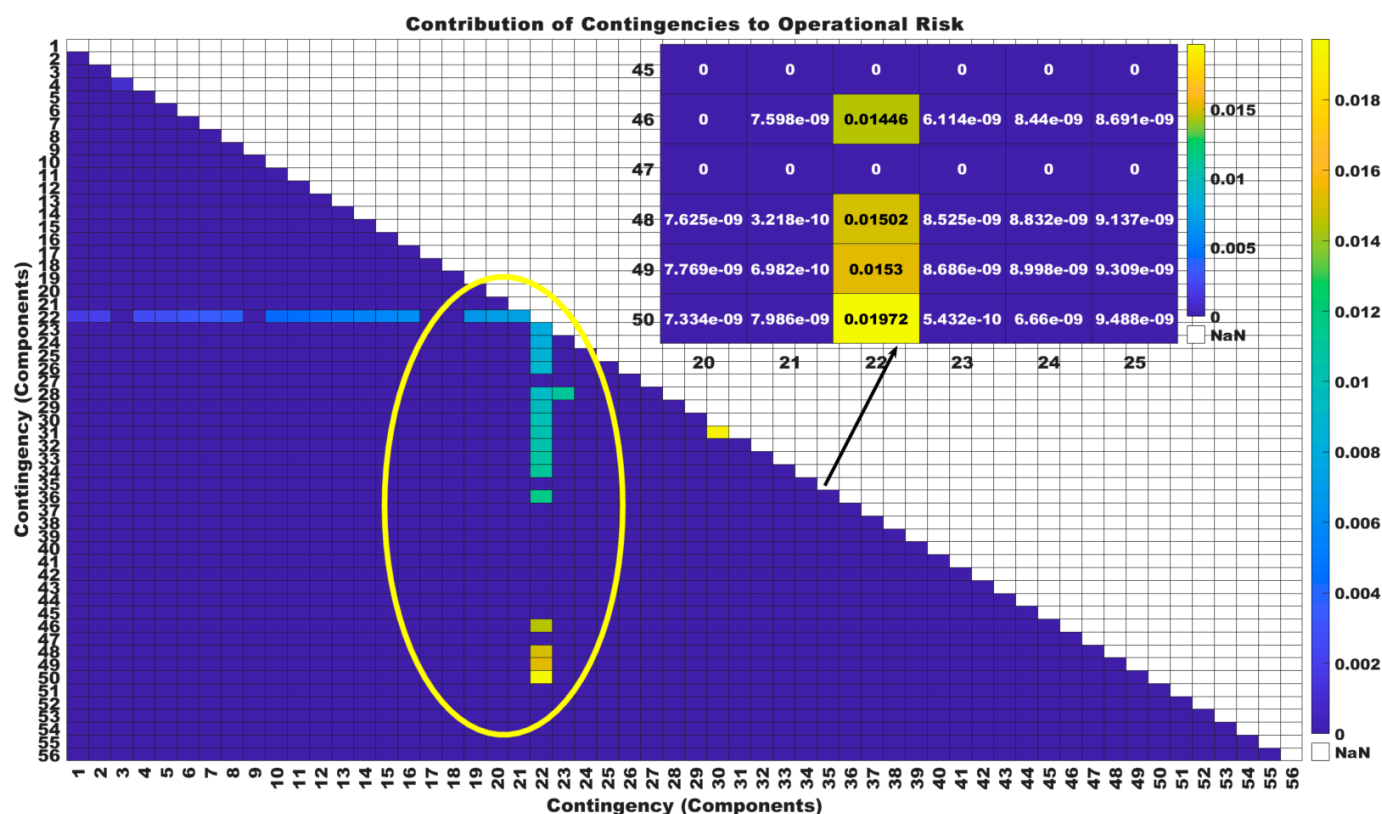


Figure S10. Contribution of overvoltage contingencies at 80%–GLM.

3.2. Operational Risk of Over-Voltage Result Visualization through Risk-based Contingency Chart

Heat-maps through which probabilistic behaviour of contingency is incorporated and the deterministic contribution to the respective operational risk is presented, in overvoltage case as the generation loading level is increased the significant amount of contributing contingency to the operational risk of overvoltage is decreasing depicted in Figure (S11–S13). Instead from the risk-based aspect any type of contingent event can be noticed. For instance at second operating condition (Figure S11) MIMP, and MIHP contingent events are present, although at second operational condition number of contributing contingencies are decreasing but mainly the impact has been increased from low to medium. In third operating condition (Figure S12) predominant contingency categories are similar as with the standard or first operational scenario where the generation loading level is at its standard value like LIMP, LIHP, HIMP. Instead in operating condition 4 (Figure S13) where the generation loading level is at its peak value mainly LILP, HIMP, HIHP categories of contingent event can be noticed.

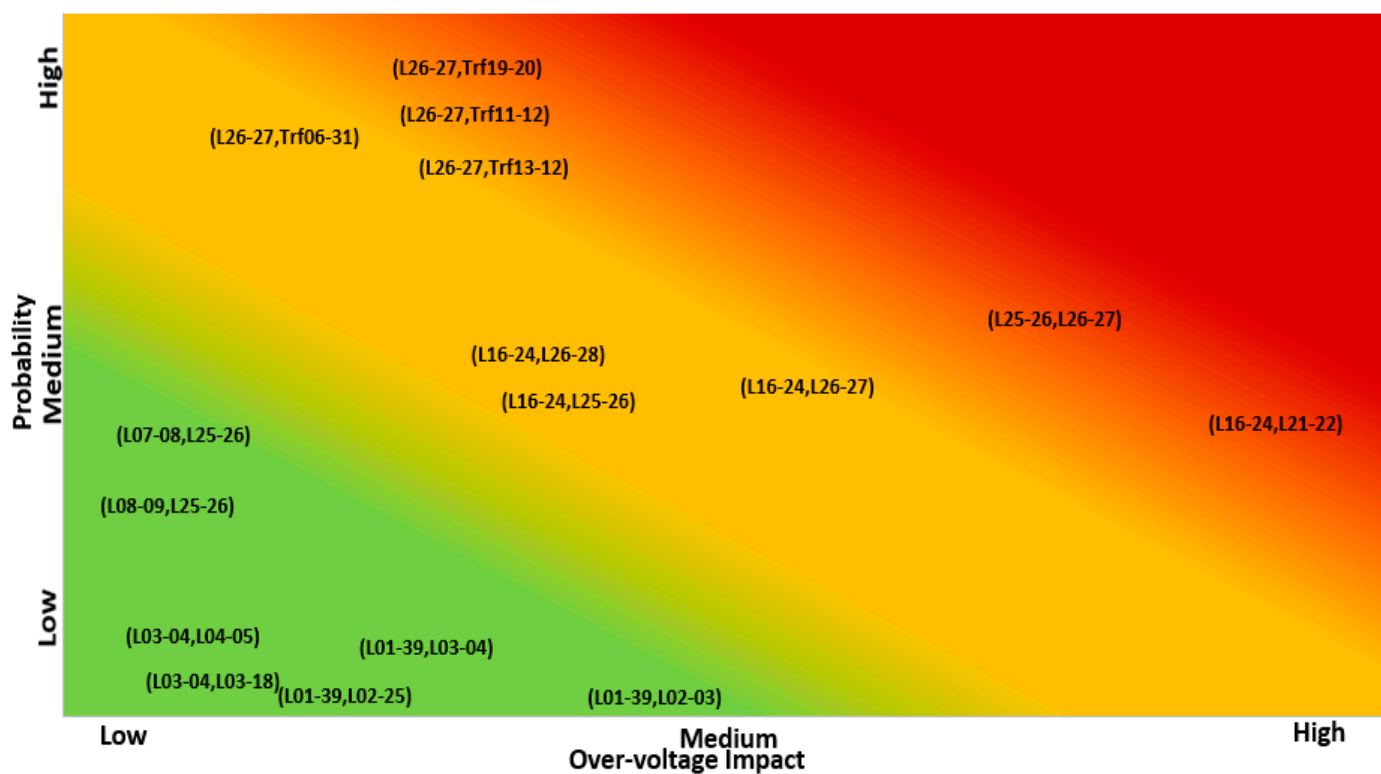


Figure S11. Over-voltage Risk-based contingency chart under 2nd operating condition.

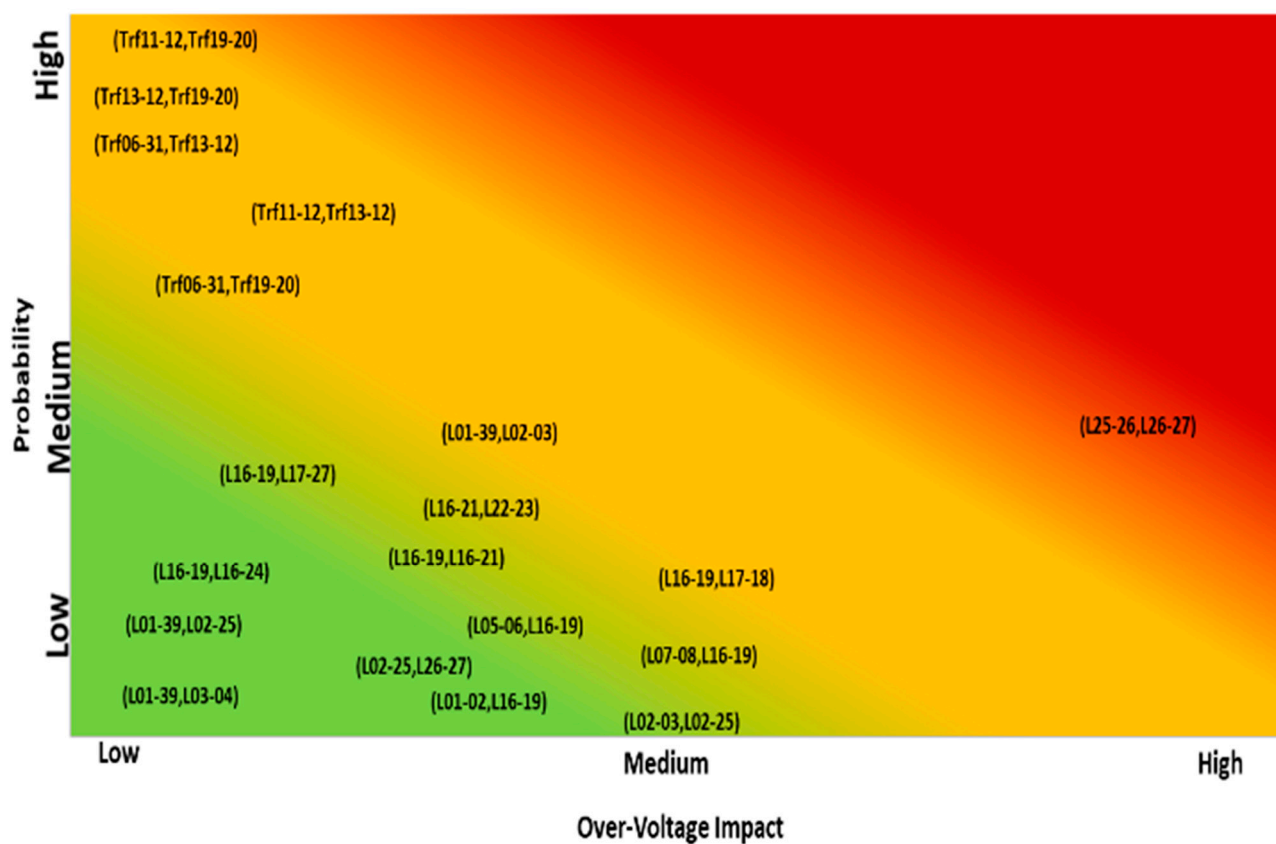


Figure S12. Over-voltage Risk-based contingency chart under 3rd operating condition.

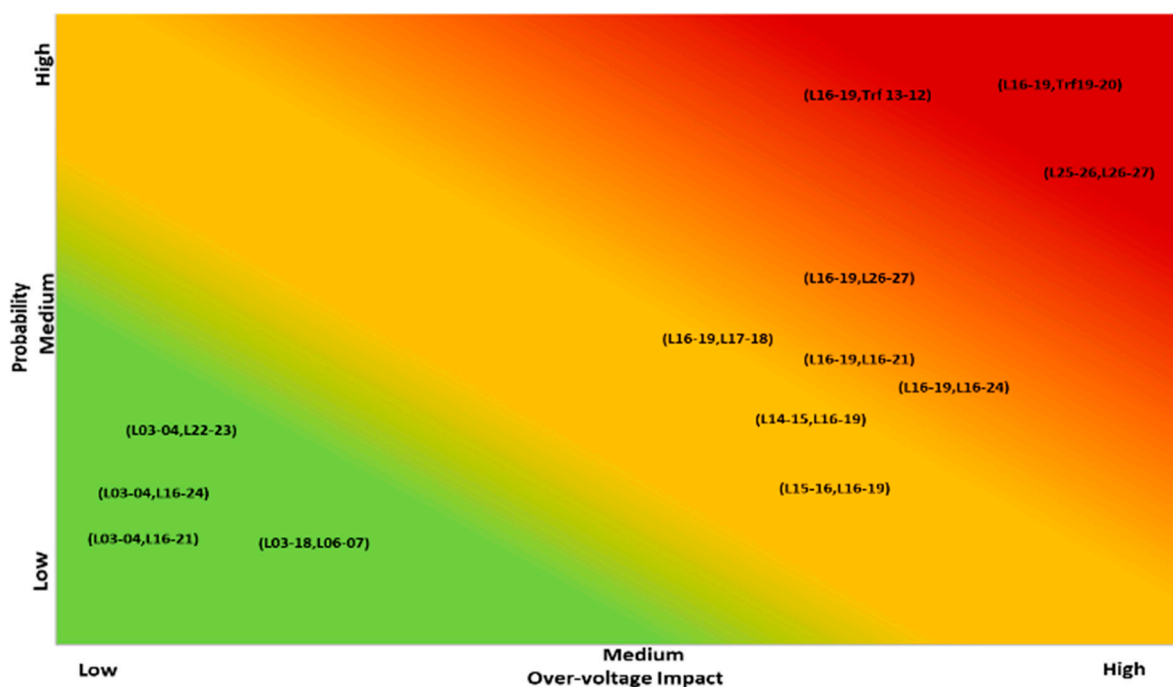


Figure S13. Over-voltage Risk-based contingency chart under 4th operating condition.

4. Contingency Pattern in Operational Risk of Under-Voltage

Here in this section contingencies behaviour of undervoltage is discussed for the remaining three operational conditions.

4.1. Contingency Pattern Visualization through Heat-Map

4.1.1. 2nd Operational Condition (40% Increment in GLM)

In the 2nd operational scenario when the generation loading level reaches up to 40%, although by maintaining the balance between generation and loading, the extreme-loading and undervoltage problems are rising and can lead to the system collapse condition in the grid. According to the expectation, the number of contingency cases and their impact on various busses are increasing. And here in this case TSO has to pay special attention to those contingency cases in which component numbers 27, 36, 37, 39, and 43 are involved depicted in Figure S14. For instance, contingency number 1121, (27,43) when (Line 21-22, G-09) failure are involved. This contingent event has a medium probability of occurrence (not high not low) i.e., 0.4137 and has a high impact of 4.582 p.u. more than the standard operational scenario. This contingent event is creating more undervoltage at various buses e.g., Bus number 38 will face 0.710 p.u. undervoltage, Bus-29 experience 0.727 (p.u.), Bus-28 face 0.729 and Bus-27 experiences 0.790 p.u. instead the threshold of undervoltage is set upto the 0.95(p.u.). In standard operational conditions, different busbar experience a maximum of 0.89p.u. undervoltage, but now in this operational scenario bus bars facing more undervoltage. Similarly, contingency number 1331 in which component numbers (36,37), (G02-G03) are involved, a contingent event also has a medium probability of occurrence (0.4636) and has a high impact 3.8621 p.u., and is creating undervoltage even 0.683p.u. at Bus-31, 0.704 p.u. at Bus-32, 0.709 p.u. at Bus-08, 0.712 p.u. at Bus-07, 0.731p.u. at Bus-12, 0.734 p.u. at Bus-05, 0.745p.u. at Bus-11 and so on.

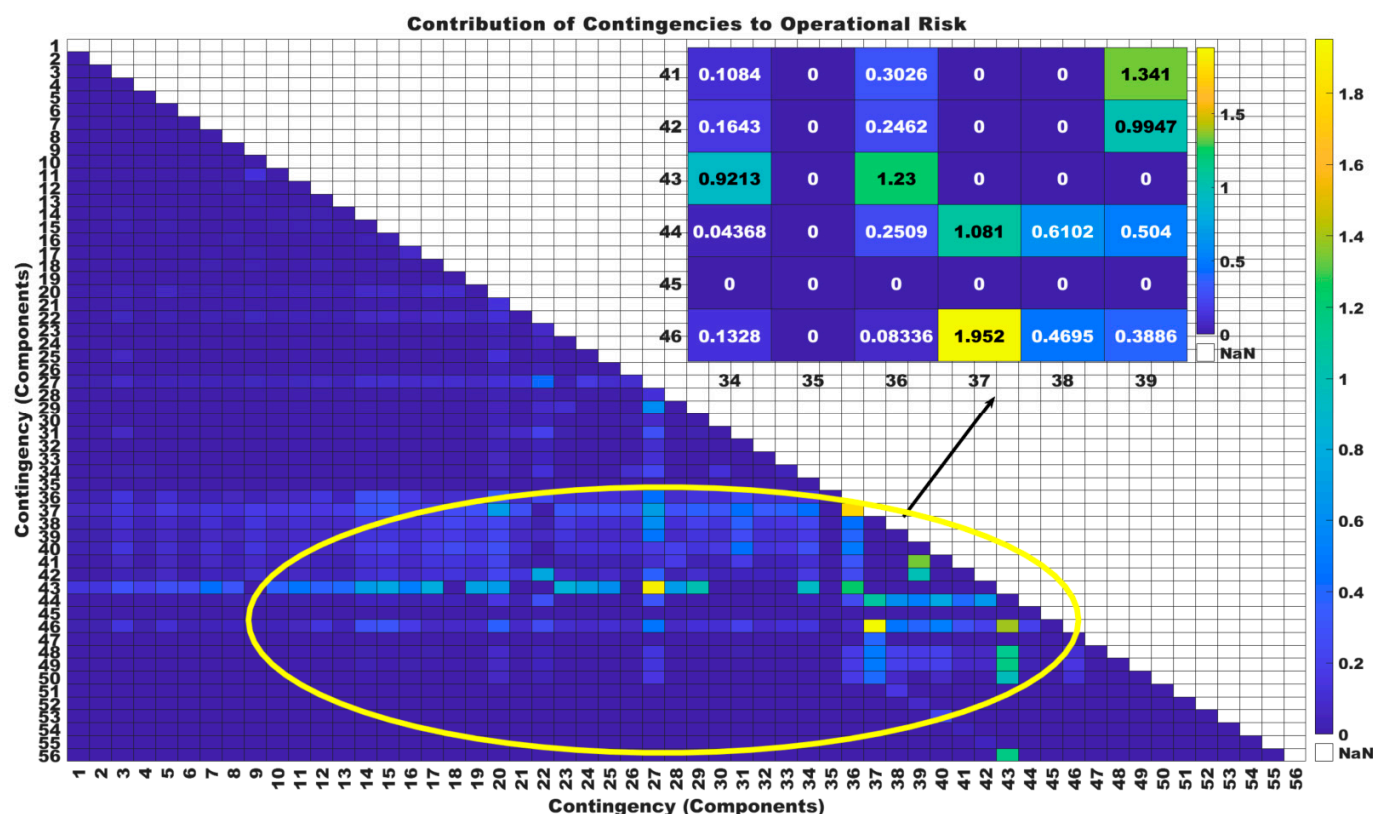


Figure S14. Contribution of under-voltage contingencies at 40%-GLM.

4.1.2. 3rd Operational Condition (60% Increment in GLM)

In the 3rd operational scenario when the generation loading mix reaches up to 60% the number of contingency cases increased as depicted in Figure S15. Now in this operating condition, the most impactful contingency is changed i.e., contingency number 1437 (42, 44) has a high impact i.e., 3.1175 p.u. and has a high probability of occurrence 0.6195. TSO has to pay attention to those contingency cases in which components (27, 31, 34, 42, 44, 46) are involved, refer to Figure S15, it can be noticed that these contingent components are taking high contribution towards the undervoltage operational risk. By doing undervoltage network studies this contingency number 1437 (G08–G11) creating undervoltage 0.774 p.u. at Bus-07, 0.778 p.u. at Bus-08, 0.782 p.u. at Bus-05, 0.785 p.u. at Bus-06, 0.797 p.u. at Bus-04 and so on.

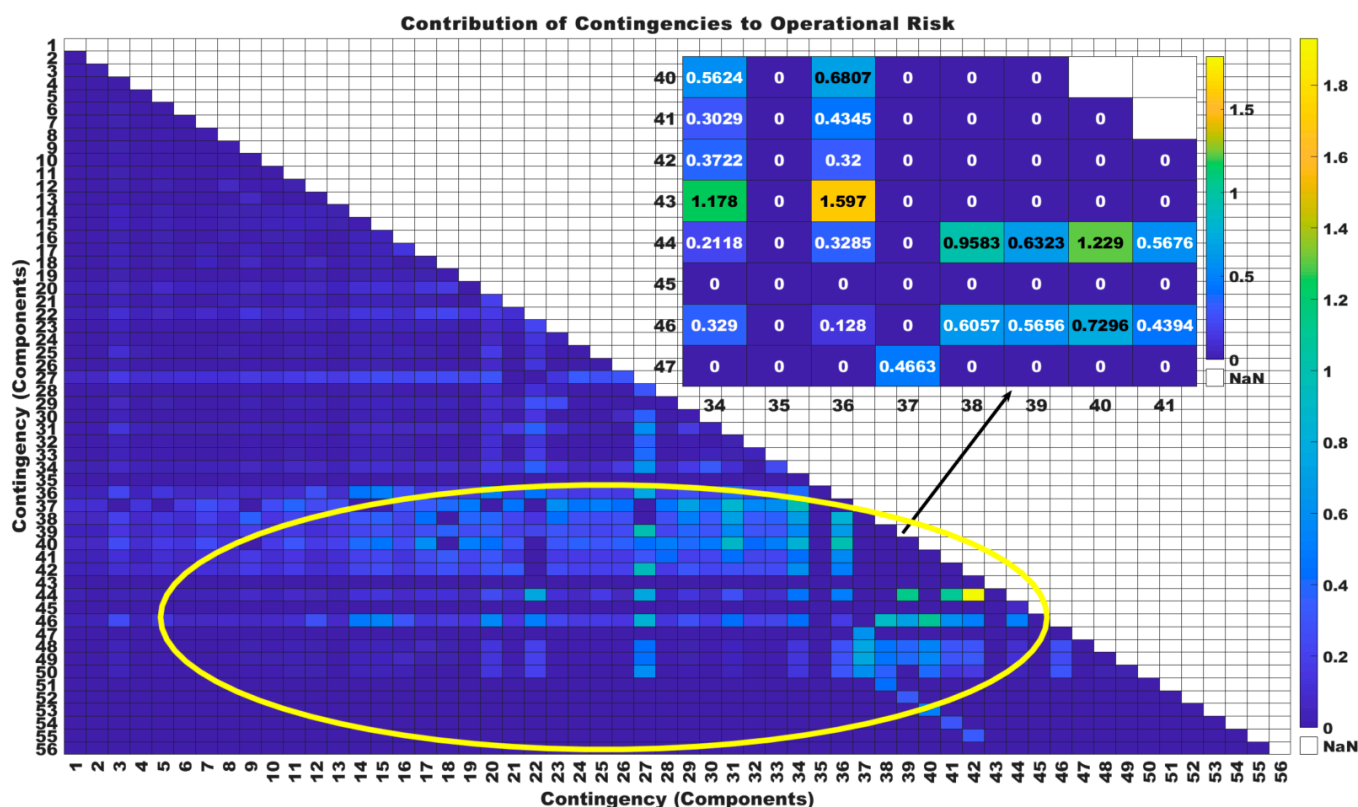


Figure S15. Contribution of under-voltage contingencies at 60%-GLM.

4.1.3. 4th Operational Condition (80% Increment in GLM)

In the 4th operational scenario number of contributing contingency cases are less as compared to the previous operating condition depicted in Figure S16. Nevertheless, the main reason for this phenomenon i.e. (few-contingency but with extremely high impact) is that many contingent events cannot even converge due to the extreme undervoltage impact and leads to the system collapse risk. In this condition, contingencies are even creating 0.4 p.u. undervoltage at different buses which is a very serious operational security threat for the grid.

TSO has to pay special attention on those contingency events in which component numbers, 38 (G-04), 40 (G-06), 46 (Trf 06-31), 48 (Trf 11-12) and 49 (Trf 13-12) are involved as depicted in Figure S16.

Because these components failures are taking high contribution to the operational risk of under-voltage. For instance, contingency number 1377 (38, 46) (G-04, Trf 06-31) are involved. This contingency event has a high probability of occurrence 0.5900 and has a high impact i.e. 3.495 p.u. and create an undervoltage problem at many bus bars during lead time. For instance, it creates 0.690 p.u. undervoltage at Bus-08, 0.702 p.u. at Bus-07, 0.735 p.u. at Bus-05, 0.740 p.u. at Bus-06, 0.767 p.u. at Bus-04, etc.

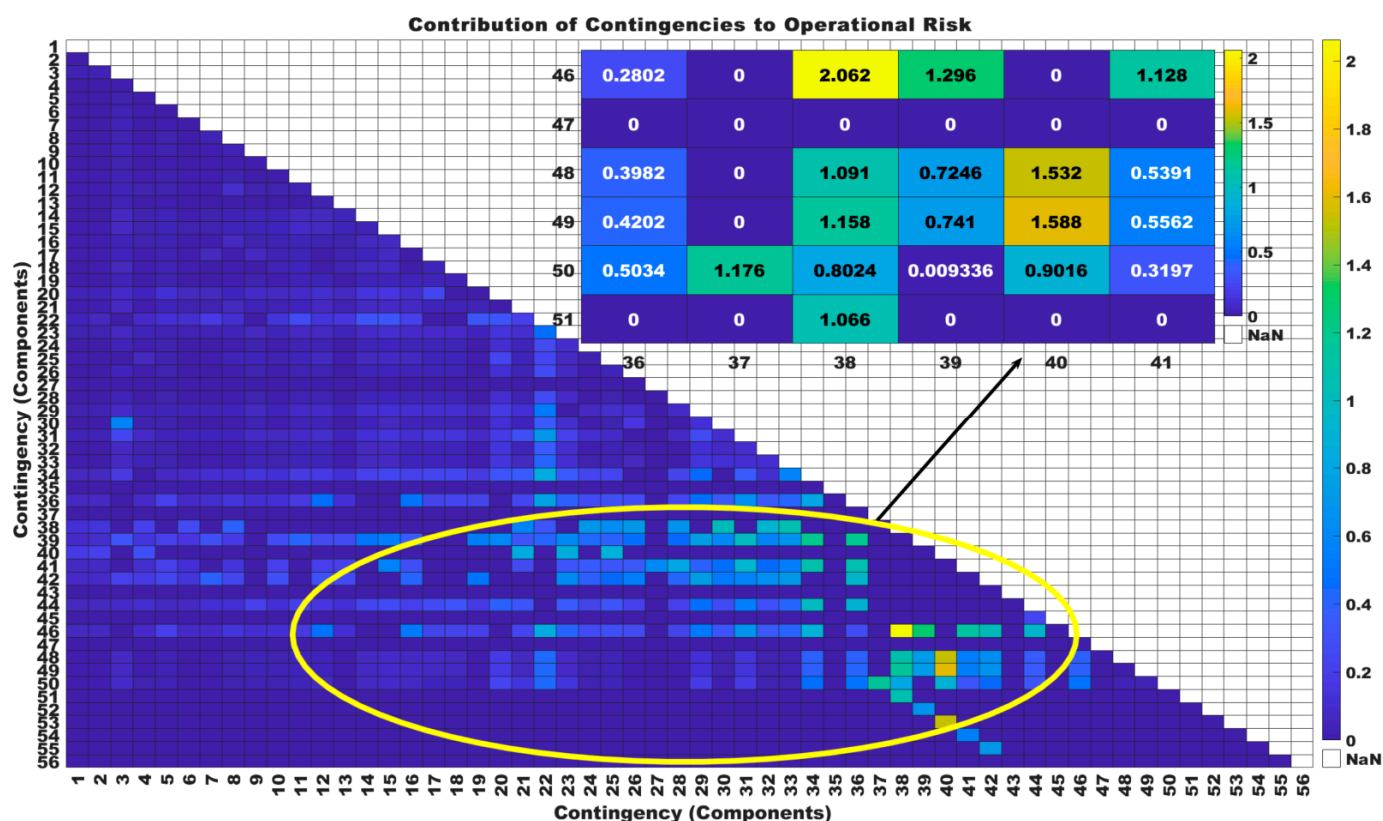


Figure S16. Contribution of under-voltage contingencies at 80%-GLM.

4.2. Operational Risk of undervoltage

As the operating condition changes from lower generation loading level to maximum generation loading level the number of contingencies are increasing, this increasing contingency pattern and their contribution can be noticed from the heat-maps. As the generation loading level increase upto 40% to create a second operating condition more contingency cases would appear in the yellow and red portion that shows the medium impact and medium probability contingent event (Figure S17). This risk-based chart shows that this operating condition could be dangerous for the grid operational security and many contingency events entering in to the MIMP and HIHP mode. In 3rd operating condition (Figure S18) mainly MILP, MIMP, LIHP, and HIHP these categories of contingency events can be envisioned. Instead, in 4th operating condition (Figure S19) majorly LILP, LIMP, LIHP, MIMP, MIHP, HILP contingency events can be noticed. These risk-based contingency chart shows that, during lead-time any category of contingent event could exist that could endanger the operational security of the power grid.

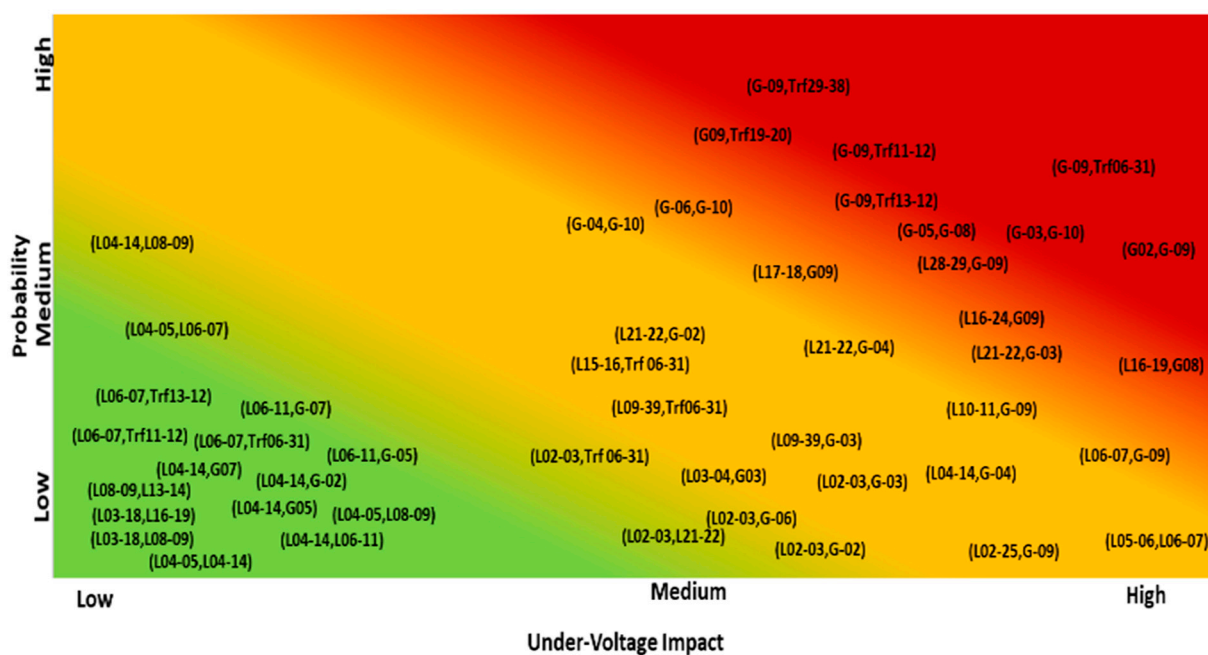


Figure S17. Undervoltage Risk-based contingency chart under 2nd operating condition.

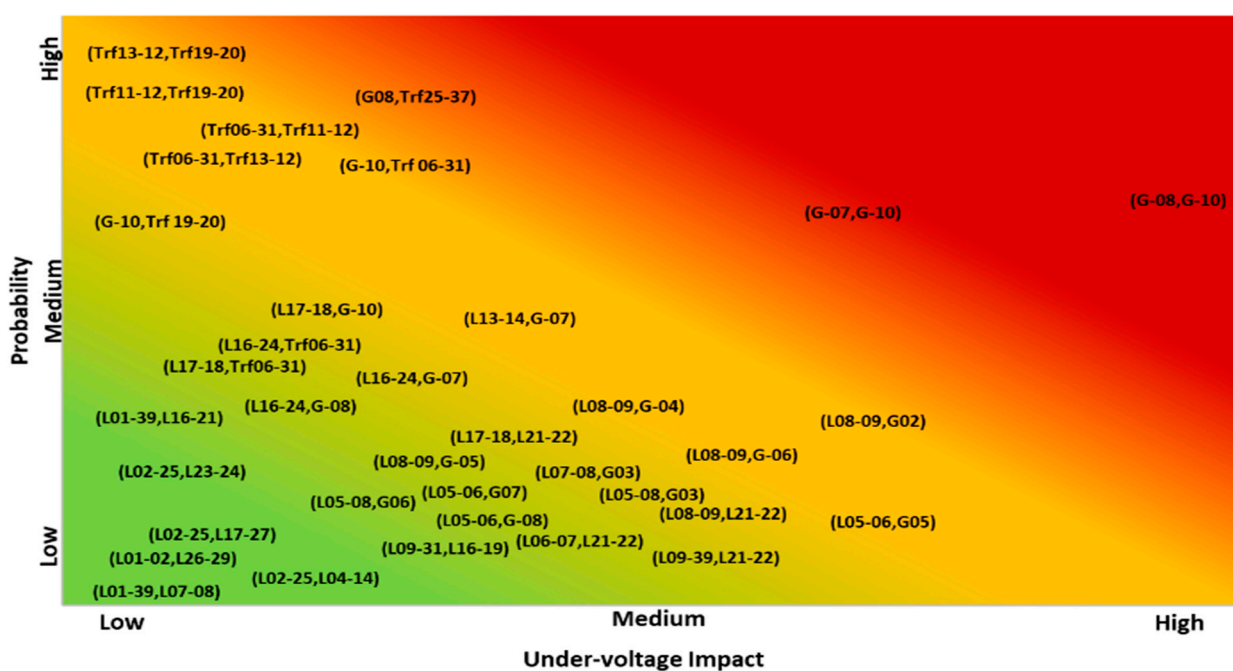


Figure S18. Undervoltage Risk-based contingency chart under 3rd operating condition.

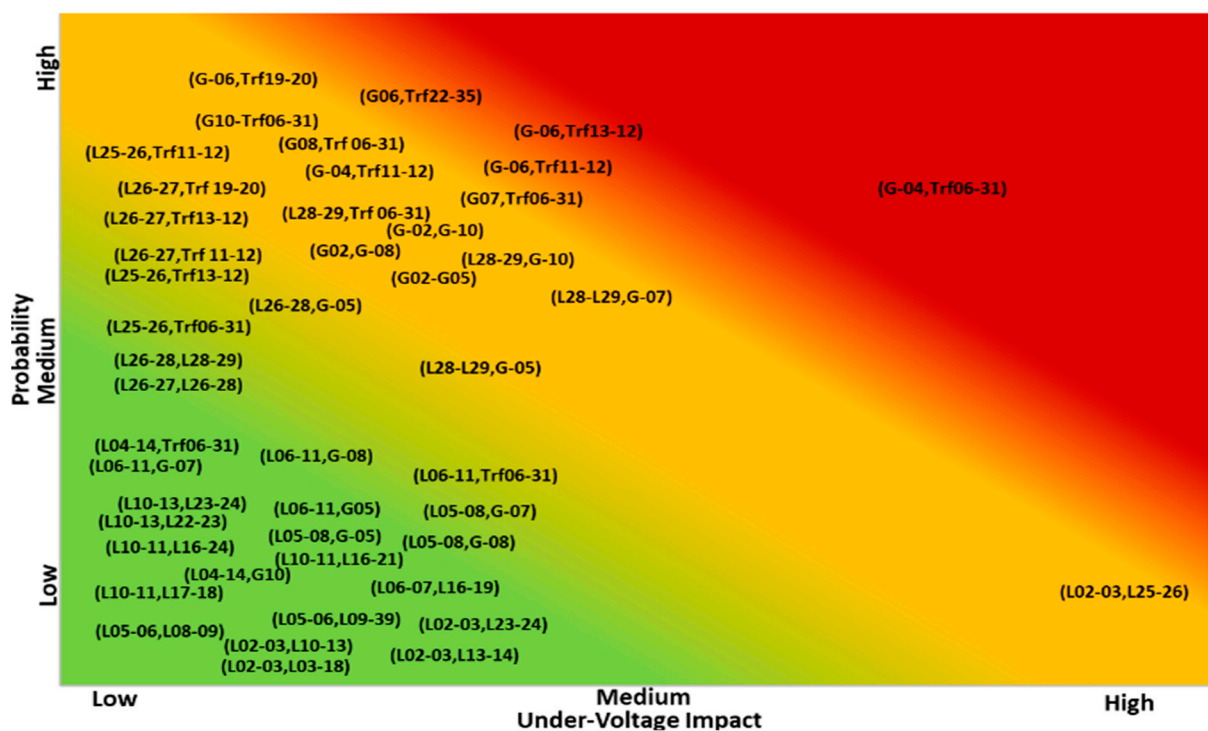


Figure S19. Undervoltage Risk-based contingency chart under 4th operating condition.

5. Contingency Pattern in Operational Risk of System Collapse

As mentioned earlier system collapse operational risks are quantified through non-convergent cases when a contingency event crosses the threshold of over-loading, under-voltage, overvoltage, then the contingency event would not converge and leads to the system collapse situation.

5.1. Contingency Pattern Visualization through Heat-Map

5.1.1 2nd Operational Condition (40% Increment in GLM)

In 2nd operational scenario, the number of non-convergent case increase according to the TSO expectation depicted in Figure S20. The overvoltage contingent events depicted from Figures S8–S10 are decreasing at this operational condition due to that more contingencies are contributing to the system collapse operational risk.

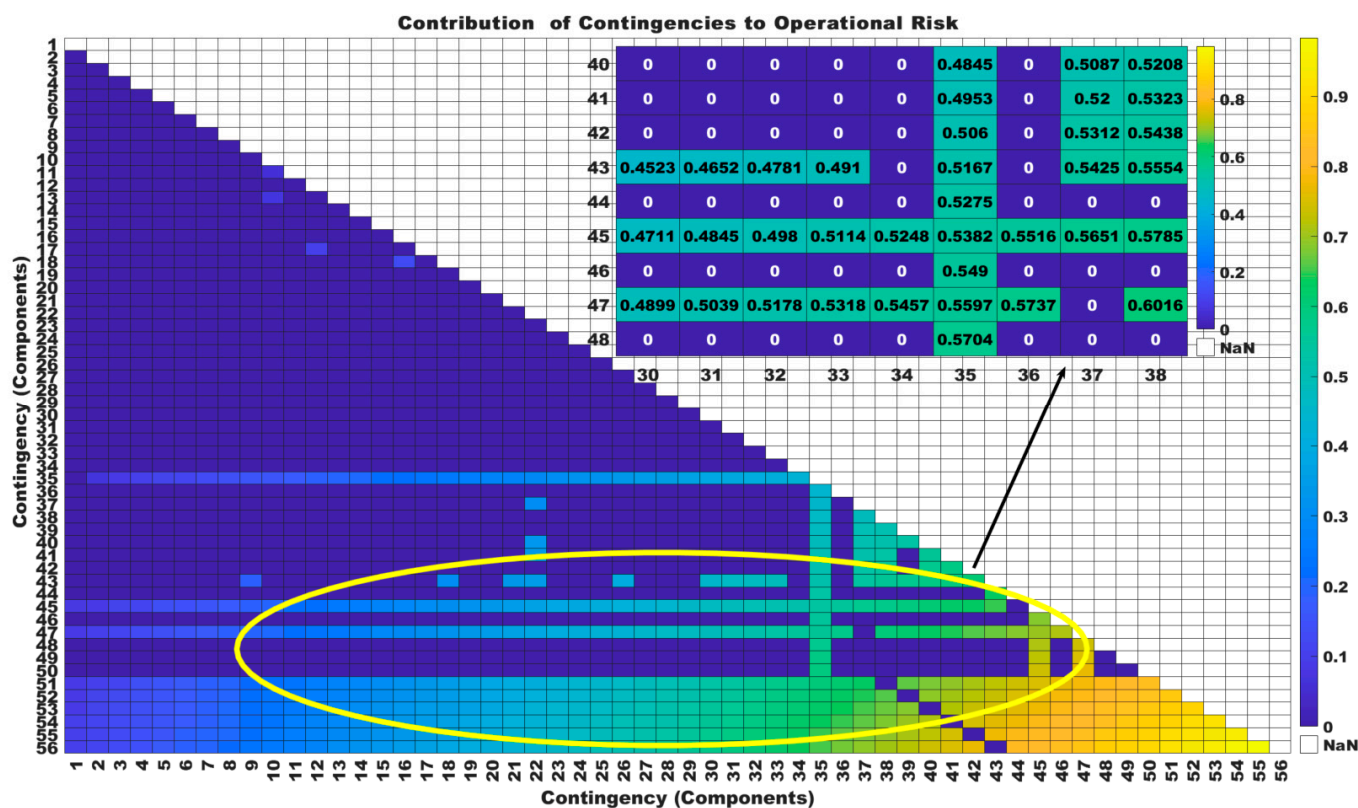


Figure S20. Contribution of system collapse contingencies at 40%-GLM.

5.1.2. 3rd Operational Condition (60% Increment in GLM)

In the third operational scenario when the generation loading level reaches up to 60% a noticeable growth in non-convergent cases can be observed. TSO has to pay special attention to those contingency cases in which component 35, 43, 45, 47 where (Line 01–02, Line 21–22), (Line 01–39, G–01), and (Line 01–02, G–09) etc are involved.

The lower contingency number in which the starting index components are involved has less probability of occurrence as compared to the higher contingencies number. And this variation from lower contribution to higher contribution can be noticed in Figure S21.

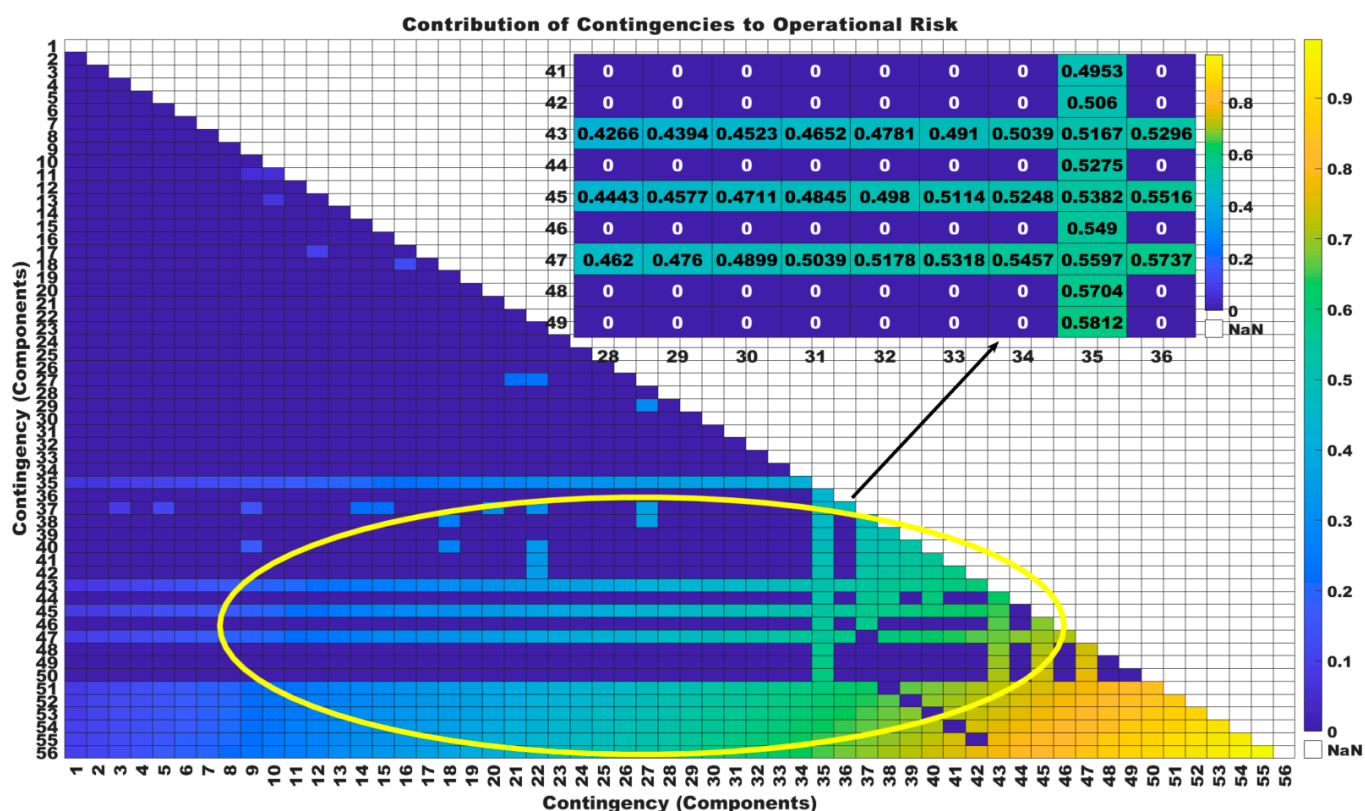


Figure S21. Contribution of system collapse contingencies at 60%-GLM.

5.1.3. 4th Operational Condition (80% Increment in GLM)

In the 4th operational scenario when the generation loading level reaches at 80%, the number of non-convergent cases increasing exponential, which tell to the TSO that it is not safe to increase as much GLM(generation loading mix) that crosses the system operational security limit and goes into partial or complete black-out conditions during the lead-time. Because blackout issues condition cannot be resolved during the lead-time. Mainly this phenomenon is the justification that why the number of contingencies cases in overvoltage, undervoltage, and extreme loading is decreasing? Because by increasing the GLM at its peak value, many contingencies are even crossing the defined numerical threshold of over-voltage, under-voltage and extreme loading and enter into the non-convergence contingency mode. That's why the less number of contingencies with high impact can be noticed in above contingencies pattern. And a large number of contingency for system collapse cases can be observed in Figure S22. This operational scenario is most dangerous among all of the above cases, which could lead to the islanding condition or complete or partial blackout, which TSO should not ignore during the operational plan.

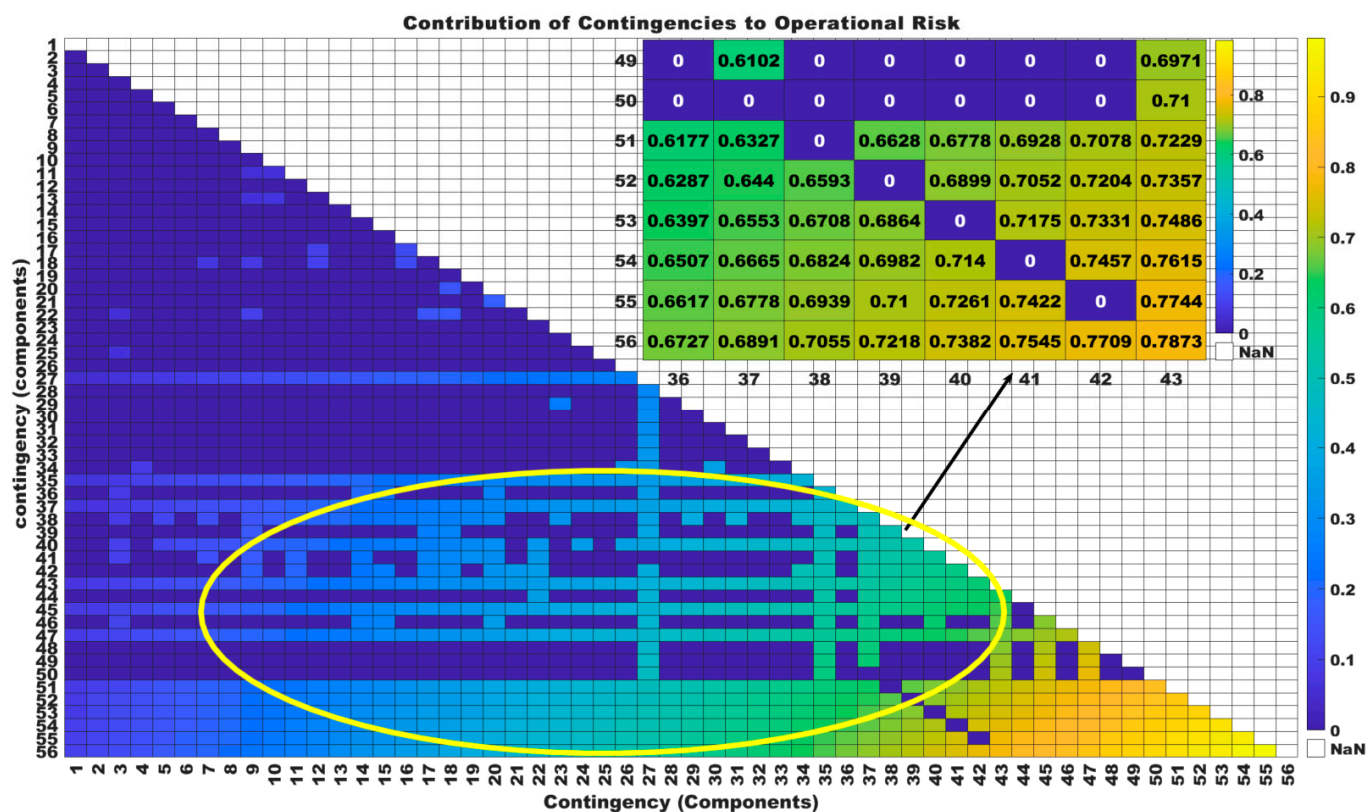


Figure S22. Contribution of system collapse contingencies at 80%-GLM.

This was the first part of the Supplementary, now in the second part Section 3. consist of a “Risk-based contingency chart” through which the grid operator can visualize the contingency event from the probability and impact aspect

5.2. Operational Risk of System Collapse

As mentioned earlier the system collapse operational risk is quantified through “non-convergence” contingency cases. But here the only matter is the occurrence of a non-convergence contingent event, mainly in all operating conditions HILP, HIMP, HIHP contingency events are present as depicted in Figures S23–S25. No LILP (low impact low probability), MIMP, MIHP contingent event cannot be noticed. That’s why all the contingency events fall in the red portion where the impact is high. In this case as the generation loading level increase, the number of appearing contingency are increasing either HILP, HIMP, HIHP justified from Figures S23,S25. TSO has to pay intensive attention to these contingency cases because the occurrence of one contingent event leads to the system collapse situation.

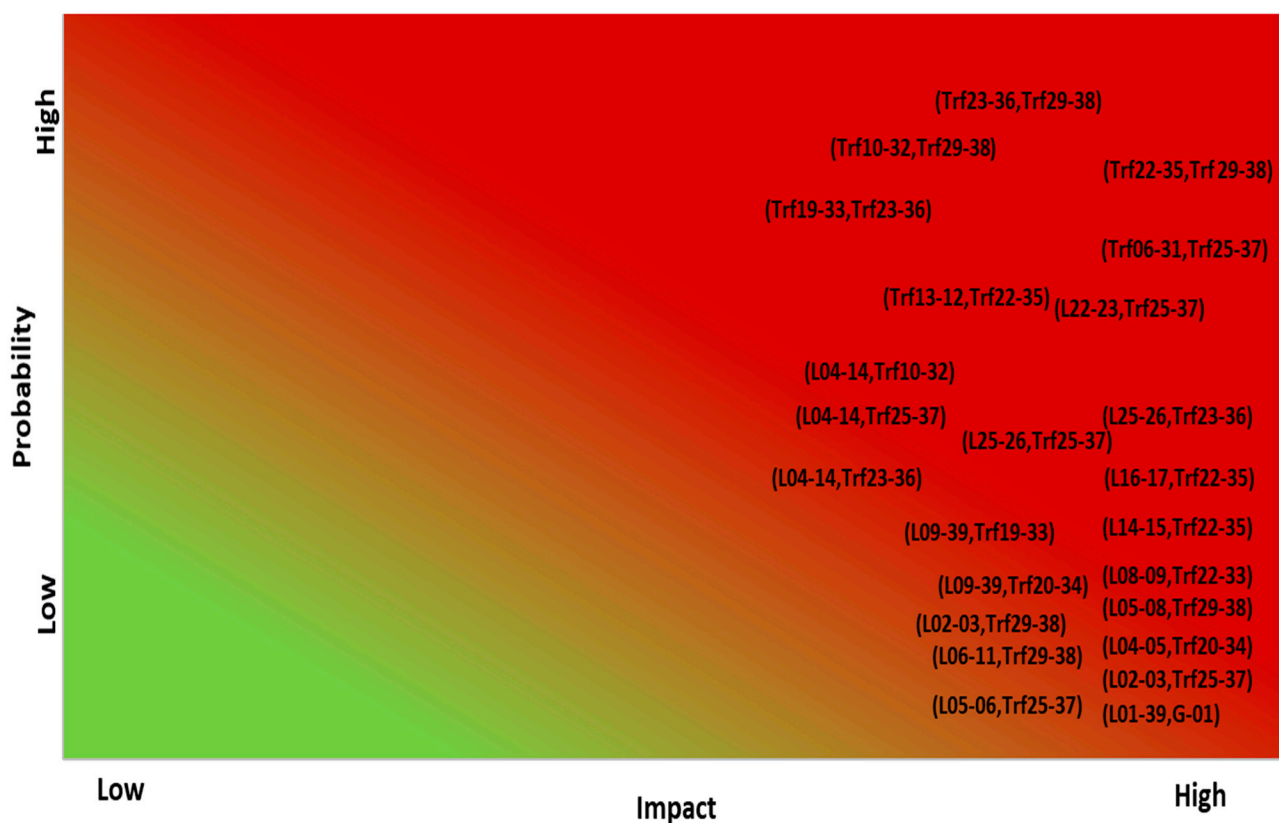


Figure S23. System collapse Risk-based contingency chart under 2nd operating condition.

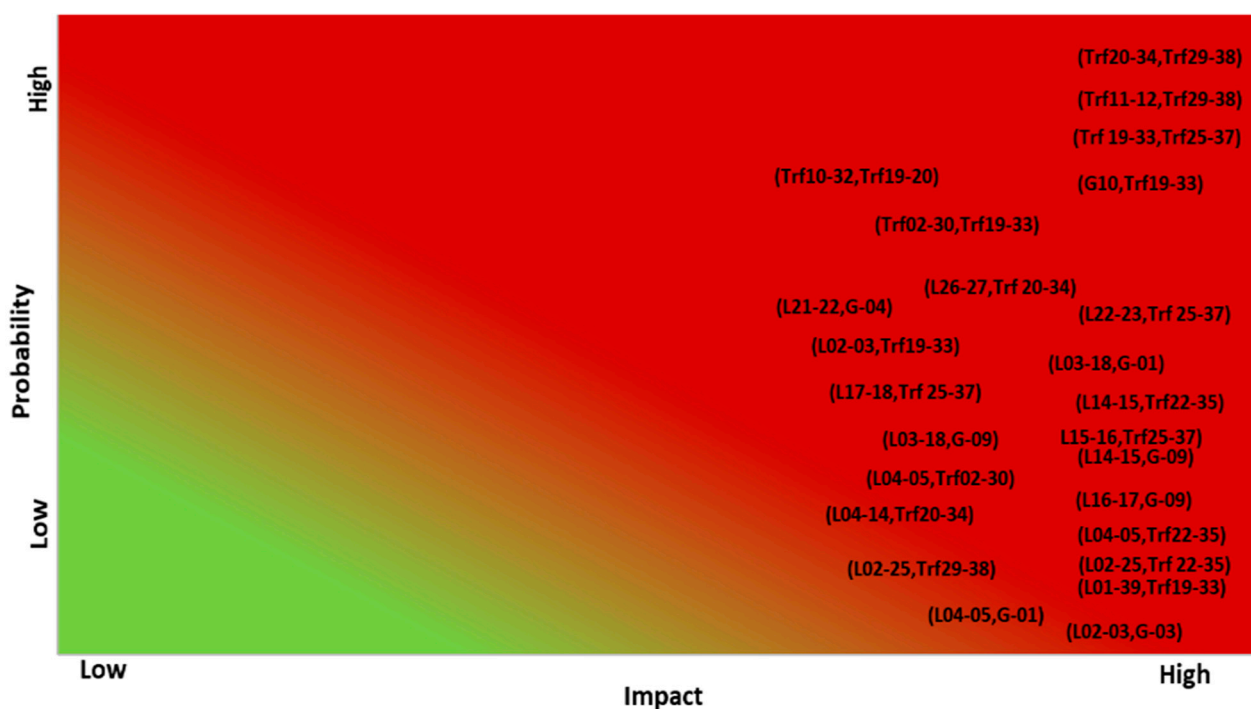


Figure S24. System collapse Risk-based contingency chart under 3rd operating condition.

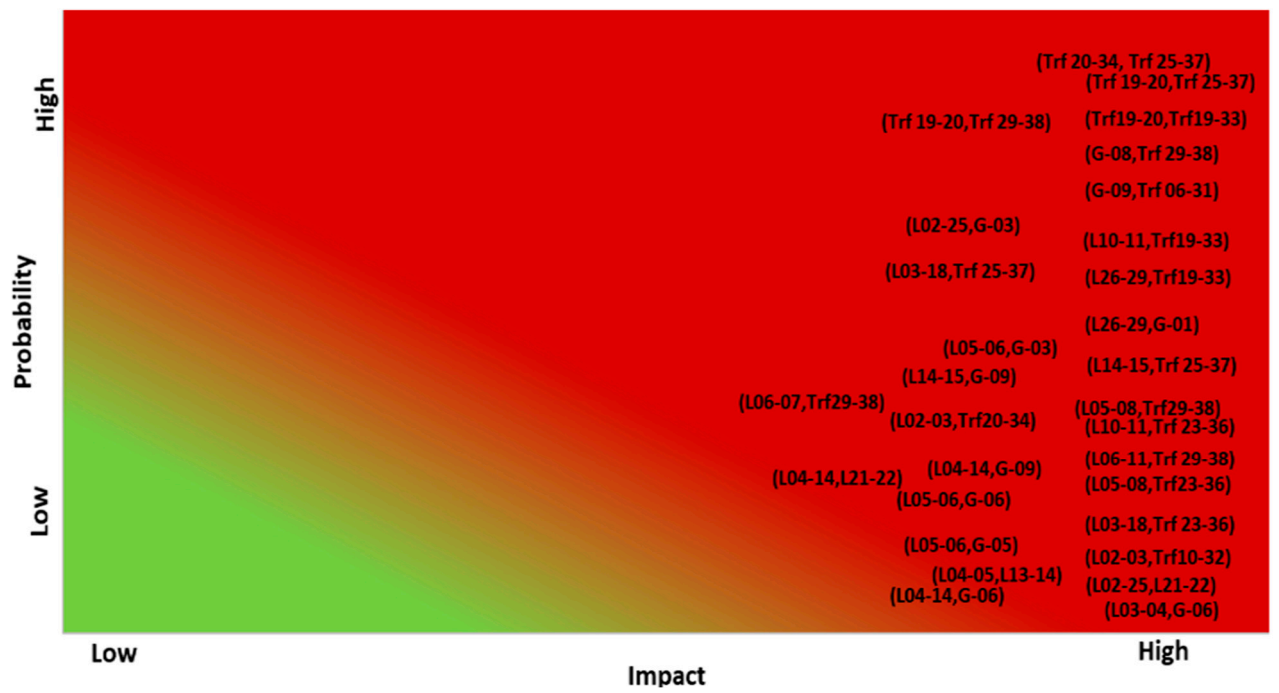


Figure S25. System collapse Risk-based contingency chart under 4th operating condition.