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Risk of Transient Stability using Rotor Trajectory Index as Severity Function

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Abstract

This paper presents a new approach to determine the risk of transient stability. It describes the implementation of rotor trajectory index (RTI) to assess the severity of power systems when it is subjected to a three-phase fault. The (RTI) is proposed as an index used to represent severity of transient instability. Risk of transient stability for three-phase fault is calculated using a well-known risk formula. Risk of transient stability provides a quantitative measure to evaluate the potential loss of synchronism of a generator that takes into account the probability and consequences. RTI index is calculated based on the machines rotor angles obtained at each step of a time domain simulation. RTI is proposed as an index to show the severity of the three-phase fault towards transient stability since it allows a fast and accurate measurement of the degree of stability of the system facing a fault. The proposed technique is implemented on the IEEE 39-bus system.

Keywords: *Trajectory Index (RTI), Severity, Risk of transient stability*

1. Introduction

Power system security refers to the ability of a power system to survive from imminent contingencies without interruption to customer service [1]. The security of a power system can be violated when it is subjected to contingencies such as line outages, line or bus fault and load variation. In the conventional power system security assessment, deterministic security limit is used and it depends on the worst-case scenario. This somehow restricts the feasible secure operating condition and hence, limits the economic potential and technical ability of power systems to supply load [2]. Furthermore, deterministic power system security assessment approach does not provide information on the condition of current operating point and the extent of security violation [3], but only provides information on whether the current operating condition is secure or insecure [4]. In the current power system environment, security assessment with respect to deterministic security boundary region is no longer relevant.

In risk based security assessment (RBSA), the risk index calculated using RBSA capture quantitatively each possible contingency occurrence probability and the event impact. Generally, the RBSA study can be grouped into risk based dynamic security assessment (RBDSA) and risk based static security assessment (RBSSA). RBDSA evaluates the risk of early swing transient stability while RBSSA studies the risk of voltage limit violation and the risk of equipment overload [5] [6].

In previous works, the risks of several security events have been addressed. This paper presents the risk of transient stability considering three-phase fault using rotor trajectory index (RTI) as a severity function. Unlike the traditional approach where the security limits are determined by the most severe contingency, in the quantification of risk, the influence of different contingencies is included. In addition, the uncertainties inherent to the transient stability assessment, such as fault location, load level and fault clearing time are also taken into account.

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2. Research Method and Materials
2.1. Risk of Transient Stability
2.1.1. Definition of Risk

RBSA has became an important task and an essential commitment and challenge in power systems field and power utility industry. The root origin of risk assessment comes from the behaviour of power systems, which is considered stochastic. Like reliability, risk have the exact same implications in which system operation with high risk level is known to be not reliable at all and vice versa. Basically risk assessment is a validation considered quantitative that includes the study of the degree of impact related to the disturbance and the contingency likelihood of every probable contingency and the degree of event impact [7]. Tables and Figures are presented center, as shown below and cited in the manuscript.

The occurrence probability of every probable contingency that create a violation of security and the event impact are been captured in a quantitative form RBSA. The two vital things to determine risk index are the probability of an event (also known as event likelihood) and the event severity (also known as impact). The calculation of risk index can be written as [8]

$$Risk = \Pr(E_i) * Sev(E_i) \quad (1)$$

Where,

E_i = contingency state

$\Pr(E_i)$ = probability of the occurrence of a contingency

$Sev(E_i)$ = severity of a contingency in a given loading condition.

2.1.2. Rotor Trajectory Index (RTI)

In transient stability studies, the trajectory of rotor angle δ_i is one of the techniques that can be used to investigate the transient stability. It is convenient to use center of inertia (COI) to be the reference. Machine angles related to COI are used to evaluate the stability of the system. The COI is computed as follows: [9]

$$\delta_{COI} = \frac{\sum_{i=1}^{NG} M_i * \delta_i}{\sum_{i=1}^{NG} M_i} \quad (2)$$

$$M_i = \frac{H_i}{\pi * f} \quad (3)$$

where,

δ_{COI} = inertia center angle

H_i = the machine inertia

f = the system frequency

M_i = the machine moment of inertia

δ_i = rotor angle of machine *i*

(RTI) is determined and calculated for each machine in the system individually using the machines inertias values. Each machine relative rotor angle with respect to inertia center is used to determine the transient stability. It is expressed as follows:

$$\Delta\delta_{i,COI} = \left\| \delta_i - \delta_{COI} \right\| \le \delta_{\max} \quad (4)$$

For i=1 to NG

where,

$\Delta\delta_{i,COI}$ = difference between rotor angle and inertia center angle.

δ_i = rotor angle of machine *i*
δ_{COI} = inertia center angle
$\delta_{\max}$ = maximum angle difference for safe operation.
The transient stability status of a given operating point can then be deduced as follows:

$$\Delta\delta_{i,COI} = \begin{cases} \text{Transiently stable, if } \Delta\delta_{i,COI} \le \delta_{\max} \\ \text{Transiently unstable, if } \Delta\delta_{i,COI} > \delta_{\max} \end{cases} \quad (5)$$

The transient stability status of a given operating point can then be deduced as follows:
where,
$\delta_{\max}$ = Threshold value
The threshold value ranges from 0°-120° [2], but in this paper it is taken as 120°.
In this proposed work, the RTI for each generator is computed as follows [9]:

$$RTI = 1 - \frac{360 - (\Delta\delta_{i,COI})}{360 + (\Delta\delta_{i,COI})} \quad (6)$$

RTI = the rotor trajectory index
$\Delta\delta_{i,COI}$ = difference between rotor angle and inertia center angle.
$RTI > \varepsilon$ and $RTI < \varepsilon$ indicate whether the system is stable or unstable. The critical value of the threshold ε is chosen as 0.5 [9].
ε = stability threshold

2.2. Methodology

Flowchart in Figure 1 illustrates the methodology performed in this study.

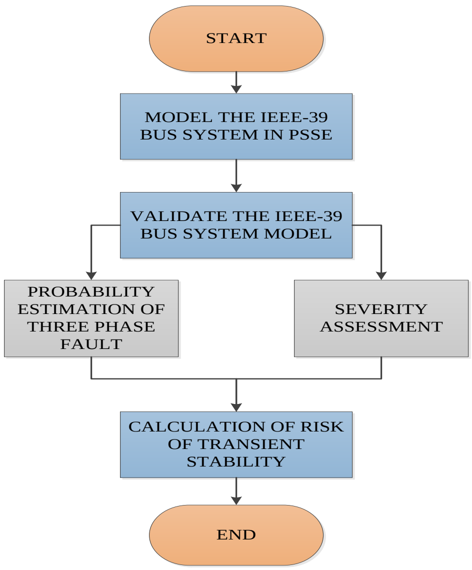

Figure 1. Procedure for calculation of risk of transient stability

2.2.1. Model Validation

The proposed methodology is implemented on a IEEE 39 bus. The test system is modeled in PSSE software. The validation of the test system model in PSSE is performed by ensuring the following criteria:
(a) Machines power factor should be more than 0.85.
(b) Systems total mismatch should be closed to zero.
(c) Bus voltage limit must not be violated.

2.2.2. Probability Estimation

In this study, the uncertainty considers is the occurrence of three-phase fault. Three-phase fault is applied to line and bus in the test system. The typical probability of occurrence of three-phase fault is 0.02 [10]

2.2.3. Severity Assessment

The severity of a contingency towards transient stability is computed as follows:

$$Sev = Max(RTI) \tag{7}$$

The RTI calculated using (6) is used to reflect the severity of a given contingency towards transient stability. It is chosen as an index to reflect the severity due to the following advantages:

(a) It can clearly define the boundary of stability and the security limit.
(b) It is easy to calculate.

3. Severity Assessment

The analysis are divided into the following scenarios:

a. Risk of Transient Instability Due to Line fault
b. Risk of transient stability due to line fault at base case
c. Risk of transient stability due to line fault with load variation
d. Risk of Transient Instability Due to Bus Fault
e. Risk of transient stability due to bus fault at base case
f. Risk of transient stability due to bus fault with load variation.

3.1.1. Risk of Transient Stability Due to Line Fault at Base Case

A three-phase fault is applied at 23 lines in the IEEE-39 bus system, which gives a 23 different cases. In each case, the fault is cleared at four different fault clearing time (FCT) for the purpose of analyzing the transient stability condition and RTI values were calculated. The transient stability of an operating system is determined by the maximum RTI which is the severity in the risk calculation in this case As in equation (7).

Table 1, shows the severity of a three phase fault occurred at lines in base case load condition. The three phase fault is considered transiently unstable if the severity value is more than 0.5. The unstable case value is bolded in black.

Table 1. Severity of three phase line fault at base case condition

Faulted Line	Severity			
(From bus-to bus)	FCT = 0.3 s	FCT = 0.4 s	FCT = 0.5 s	FCT = 0.6 s
4-14	0.336029	0.417808	0.572813	1.927858
10-13	0.49081	1.973247	1.973589	1.974864
15-14	0.337886	0.378318	0.41837	0.458102
18-17	0.37163	0.425407	0.479478	0.532909
25-2	1.79524	1.826815	1.853014	1.860932
26-29	1.830748	1.832243	1.843415	1.843505
27-17	1.60792	1.712728	1.715626	1.716248
4-5	0.328378	0.419643	0.589752	1.852601
8-5	0.331765	0.383033	0.502381	1.942087
8-9	0.357805	0.415795	0.495888	1.713463
11-10	0.405179	1.977067	1.978702	1.97886
13-14	0.403205	1.970275	1.973918	1.974265
16-21	0.444813	0.611724	1.770857	1.839611
21-22	0.378049	0.477781	1.938839	1.942075
23-24	0.486255	1.873732	1.887277	1.887287
1-2	0.269681	0.28165	0.293134	0.303962
3-18	0.361533	0.411455	0.460751	0.507701
6-11	0.364951	1.976734	1.979824	1.979853
7-6	0.327795	0.377714	0.459188	1.892916
9-39	0.257152	0.270709	0.28331	0.294698
19-20	1.83661	1.83761	1.93428	1.947643
26-27	1.753738	1.777632	1.779288	1.796845
26-28	1.777067	1.77947	1.797721	1.798607

The risk of transient stability for each three-phase line fault for different FCT is shown in Figure 2.

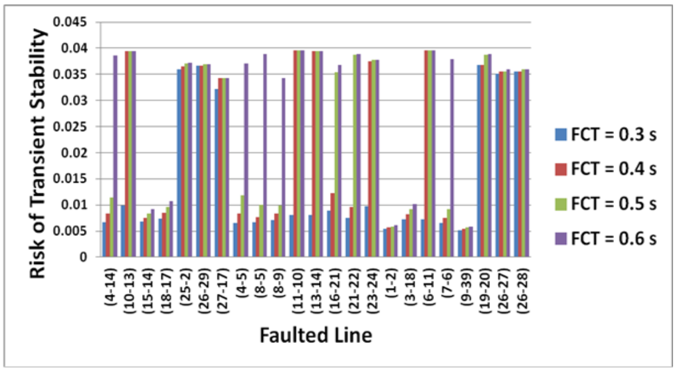

Figure 2. Risk of transient stability due to line fault at base case condition

From Figure 2, it can be observed that the risk of transient stability of due to a three-phase line fault have a proportional relationship with FCT. Three-phase line fault occurred at 25-2, 26-29, 27-17, 19-20, 26-27 and 26-28 lead to higher risk. It is also noted that the risk of transient stability increases as the FCT of the fault is increased. It implies that an operating system become more risky if the fault is allowed to sustain in the system for a longer period of time.

3.1.2. Risk of Transient Stability Due to Line Fault with Load Variation

Table 2 to Table 5 show the severity of three-phase line fault towards transient stability at different load conditions with FCT of 0.3s, 0.4s, 0.5s and 0.6s respectively. Active load at all load buses are increased by 30%, 40%, 50% and 60% from base case.

Table 2. Severity of three phase line fault at base case with FCT = 0.3s and load variation

Faulted Line (From bus-to bus)	Load Increase			
	30%	40%	50%	60%
4-14	0.3986	0.4460	1.8987	1.9119
15-14	0.3541	0.3924	0.4315	1.9066
4-5	0.3793	0.5409	1.7883	1.9163
8-5	0.4034	0.4679	1.9201	1.9522
11-10	1.9451	1.9475	1.9856	1.9867
16-21	0.3360	1.7869	1.8236	1.9229
3-18	0.3833	0.4199	1.8972	1.9065
6-11	1.9866	1.9876	1.9879	1.9900
7-6	0.3638	0.4727	1.9296	1.9344
9-39	0.2461	0.2668	0.3304	1.9207

Table 2 shows the severity 10 three-phase line faults at different load conditions. It can be seen that load increased beyond certain limit caused the machines' rotor angle to diverge hence, leading to loss of synchronism. Three-phase line fault that occurred at 11-10 and 6-11 are the most severe contingency since the maximum RTI is greater than 0.5 even at 30% load increment which indicate transient instability when the FCT is set at 0.3s. The severity towards transient stability increases as the load increased.

The severity of 8 three-phase line fault towards transient stability with FCT=0.4s are shown in Table 3. In this case, 5 three-phase line faults (i.e. 4-14, 4-5, 8-5 16-21 and 7-6) have severity of more than 0.5 at 30% load increased. Three-phase line fault at 4-14 is transiently stable at 30% load increased if the fault is cleared within 0.3s (refer to TABLE 2), however it becomes transiently unstable if it is cleared at a longer FCT (e.g. 0.4s). The system becomes more vulnerable to transient stability if the fault is allowed to sustain at a longer duration.

Table 3. Severity of three phase line fault at base case with FCT= 0.4s and load variation

Faulted Line (From bus-to bus)	Load Increase			
	30%	40%	50%	60%
4-14	1.8845	1.9083	1.9283	1.9356
15-14	0.3541	0.4112	0.4522	1.9356
4-5	1.7670	1.8813	1.8833	1.9176
8-5	1.8914	1.9023	1.9249	1.9569
16-21	1.77	1.820	1.910	1.950
3-18	0.425	1.8796	1.8984	1.8992
7-6	1.9196	1.9266	1.9396	1.9454
9-39	0.2700	0.2807	0.3422	1.9331

Table 4. Severity of three phase line fault at base case with FCT= 0.5s and load variation

Faulted Line (From bus-to bus)	Load Increase			
	30%	40%	50%	60%
15-14	0.3920	0.4620	0.4860	1.9620
3-18	1.8757	1.8875	1.9024	1.9054
9-39	0.2794	0.2972	1.9067	1.9444

Table 5. Severity of three phase line fault at base case with FCT= 0.6s and load variation

Faulted Line (From bus-to bus)	Load Increase			
	30%	40%	50%	60%
15-14	0.4750	0.4850	0.4920	1.980
9-39	0.3065	0.3137	1.9170	1.9448

In Table 4 and Table 5, similar interpretation can made with the previous simulation when the FCT is set to 0.5s and 0.6s where the severity of three-phase line fault increases with load.

Figure 3 to Figure 6 show the risk of transient stability associated to three-phase line fault with different FCT. Generally, it can be seen that an operating point becomes more risky as the load increased. FCT also has an impact towards transient stability.

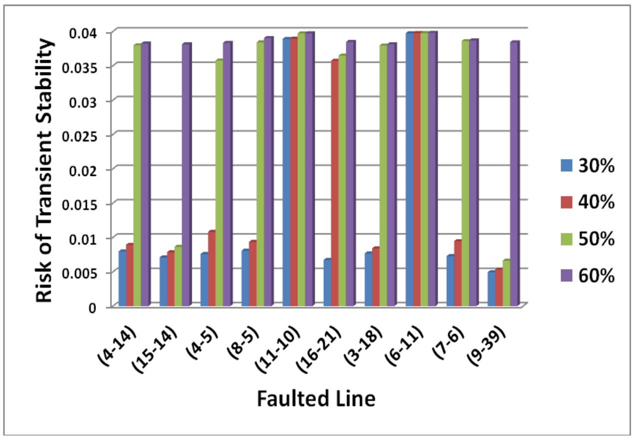

Figure 3. Risk of transient stability due to line fault with FCT= 0.3s and load variation

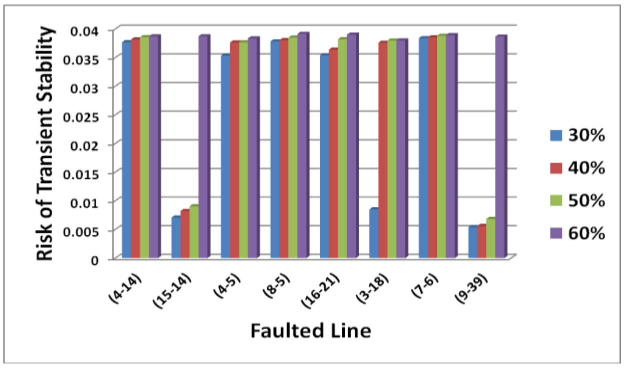

Figure 4. Risk of transient stability due to line fault with FCT= 0.4s and load variation

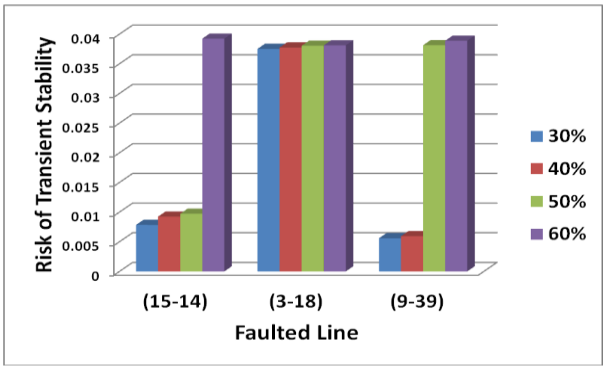

Figure 5. Risk of transient stability due to line fault with FCT= 0.5s and load variation

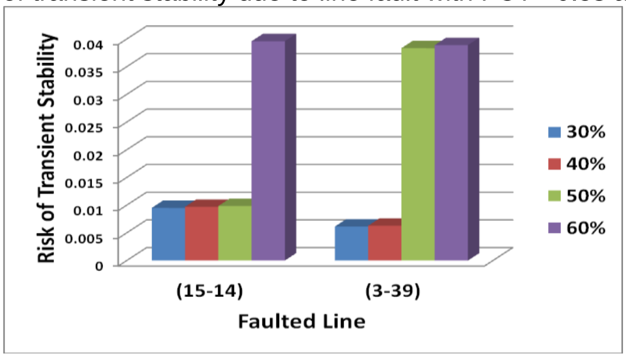

Figure 6. Risk values due to line fault with FCT= 0.6 sec and load variation

Increasing the FCT value along with increasing the load level in the system will cause instability to the system as can be seen in Figure 3 to Figure 6. Also increasing both FCT and systems loading will cause an increase in RTI index values, the maximum RTI values are used to determine the risk level as it is used as a severity function in the risk calculation formula.

3.2. Risk of Transient Instability Due to Bus Fault

3.2.1. Risk of Transient Stability Due to Bus Fault at Base Case

Table 6, shows the severity values of applying a three phase fault at a bus in the system and these values were calculated based on maximum RTI's values as severity is equal to maximum RTI. It can be seen that the severity value for each bus fault increases as FCT is increased. Increasing of fault clearing time will result in transiently unstable operating point. The unstable case is bolded in black.

Table 6. Severity of three phase bus fault at base case condition

Faulted Bus	Line Tripped	Severity			
		FCT = 0.3 s	FCT = 0.4 s	FCT = 0.5 s	FCT = 0.6 s
3	3-4	0.322657	0.35461	0.389269	0.462418
5	5-6	0.333757	1.875488	1.893455	1.898123
10	10-11	0.342514	1.978495	1.978904	1.979918
14	14-13	0.280037	0.341893	1.925701	1.972919
16	16-21	0.331857	0.527771	1.783368	1.839611
22	22-21	0.314289	0.439135	1.889006	1.940461
25	25-2	1.795234	1.851801	1.853014	1.861906
26	26-29	1.830748	1.832243	1.843415	1.843505
4	4-14	0.295012	0.375618	0.460664	1.927854
6	6-11	0.358531	1.976734	1.979845	1.979853
8	8-9	0.352169	0.415795	0.48623	1.722827
17	17-16	0.27542	0.434705	1.750744	1.774055
27	27-17	1.607921	1.712728	1.715626	1.716248
1	1-2	0.269681	0.28165	0.293133	0.303962
9	9-39	0.336029	0.336031	0.336043	0.336050
2	2-3	0.326568	0.365259	0.444998	0.602295
7	7-6	0.309627	0.374776	0.438748	1.874678
15	15-16	0.318894	0.352536	0.41716	0.465405
18	18-17	0.344527	0.380367	0.414015	0.487145
23	23-24	0.305339	1.865264	1.873732	1.887277
24	24-16	0.294681	0.364188	0.431489	0.581597
28	28-29	1.906412	1.906613	1.910378	1.910446

The risk of transient stability for each three-phase bus fault for different FCT is shown in Figure 7.

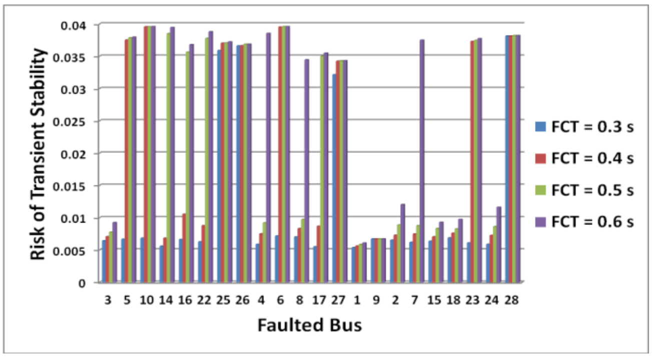

Figure 7. Risk of transient stability due to bus fault at base case condition

From Figure 7, it can be observed that the risk of transient stability of due to a three-phase bus fault have a proportional relationship with FCT. Three-phase bus fault occurred at 25, 26, 27 and 28 lead to higher risk.Again when the FCT of the fault increases, the risk of transient stability increases too. A higher risk level will occur if the system keep operating with fault on condition.

3.2.2. Risk of Transient Stability Due to Bus Fault with Load Variation

TABLE 7 to TABLE 10 show the severity of three-phase bus fault towards transient stability at different load conditions with FCT of 0.3s, 0.4s, 0.5s and 0.6s respectively. Active load at all load buses are increased by 30%, 40%, 50% and 60% from base case.

Table 7 shows the severity 8 three-phase bus faults at different load conditions. It can be seen that load increased beyond certain limit caused the machines' rotor angle to diverge hence, leading to loss of synchronism. Three-phase bus fault that occurred at 5, 6, 10 and 16 are the most severe contingency since the maximum RTI is greater than 0.5 even at 30% load increment which indicate transient instability when the FCT is set at 0.3s. The severity towards transient instability increases as the load increased.

Table 7. Severity of three phase bus fault at base case with FCT= 0.3s and load variation

Faulted Bus	Line Tripped	Load Increase			
		30%	40%	50%	60%
3	3-4	0.3626	0.3970	1.8975	1.9334
5	5-6	1.9212	1.9233	1.9288	1.9546
6	6-11	1.9825	1.9870	1.988	1.9885
10	10-11	1.9859	1.9873	1.9874	1.9881
14	14-13	0.3426	1.9237	1.9387	1.9449
16	16-21	1.8533	1.877	1.8833	1.8902
17	17-16	0.4657	1.8442	1.8532	1.8917
24	24-16	0.3769	0.4162	0.457	1.9337

Table 8. Severity of three phase bus fault at base case with FCT= 0.4s and load variation

Faulted Bus	Line Tripped	Load Increase			
		30%	40%	50%	60%
3	3-4	0.4062	1.8918	1.8989	1.9544
14	14-13	1.9171	1.9248	1.9470	1.9501
17	17-16	1.8143	1.8580	1.8634	1.9408
24	24-16	0.4911	0.9203	1.8902	1.9420

The severity of 4 three-phase bus fault towards transient stability with FCT=0.4s are shown in Table 8. In this case, 2 three-phase bus faults (i.e. 14 and 17) have severity of more than 0.5 at 30% load increased. Three-phase bus fault at 14 is transiently stable at 30% load increased if the fault is cleared within 0.3s (refer to Table 7), however it becomes transiently unstable if it is cleared at a longer FCT (e.g. 0.4s). The system becomes more vulnerable to transient instability if the fault is allowed to sustain at a longer duration.

Table 9. Severity of three phase bus fault at base case with FCT= 0.5s and load variation

Faulted Bus	Line Tripped	Load Increase			
		30%	40%	50%	60%
3	3-4	1.889	1.900	1.9100	1.9760
24	24-16	1.2055	1.6421	1.9120	1.9560

Table 10. Severity of three phase bus fault at base case with FCT= 0.6s and load variation

Faulted Bus	Line Tripped	Load Increase			
		30%	40%	50%	60%
3	3-4	1.9100	1.9224	1.9340	1.9890
24	24-16	1.445	1.7621	1.9520	1.9860

In Table 9 and Table 10, similar interpretation can made with the previous simulation when the FCT is set to 0.5s and 0.6s where the severity of three-phase bus fault increases with load. Figure 8 to Figure 11 show the risk of transient stability associated to three-phase bus fault with different FCT. Generally, it can be seen that an operating point becomes more risky as the load increased. FCT also has an impact towards transient stability.

Figure 8. Risk of transient stability due to bus fault with FCT= 0.3s and load variation

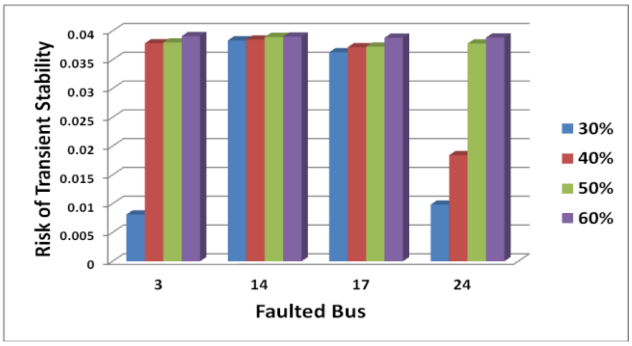

Figure 9. Risk of transient stability due to bus fault with FCT= 0.4s and load variation

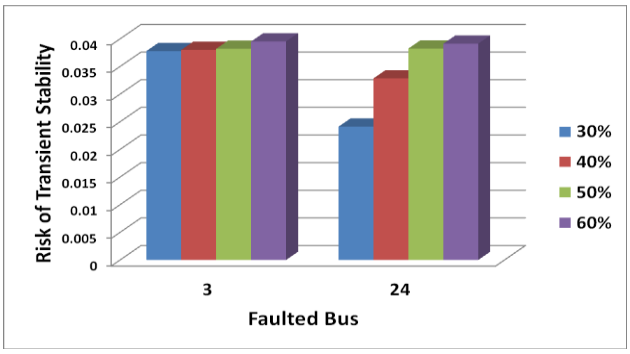

Figure 10. Risk of transient stability due to bus fault with FCT= 0.5s and load variation

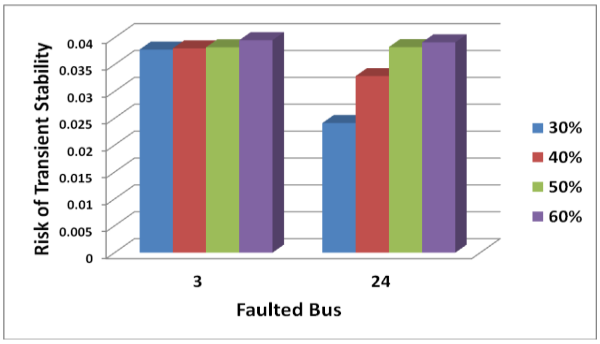

Figure 11. Risk of transient stability due to bus fault with FCT= 0.6s and load variation

4. Conclusion

This paper focuses on the risk assessment of transient stability in power systems. The uncertainties of three phase line fault and three phase bus fault have been considered. The results analysis shows that the risk of transient stability for line/bus fault increases as FCT is increased. Operating point going towards transiently unstable if the FCT is increased. It can also be seen that the FCT setting is an important factor to determine the stability of power systems. If FCT is set at a shorter time than the CCT of the line, the system is stable, otherwise the system will be unstable. RTI is an index that is used to assess the transient stability studies of a power system. In this research, RTI is proposed as the severity function of transient stability as it can quantify the extend of transient stability studies of a given operating condition. An operating condition is considered as transiently stable if the RTI is less than 0.5. The results of severity assessment for transient stability due to line fault and bus fault has been presented.

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