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Contingency Ranking Selection using Static Security Performance Indices in Future Grids

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***Abstract*—Power system security assessment and enhancement in grids with high penetration of renewables is critical for pragmatic power system planning. Static Security Assessment (SSA) is a fast response tool to assess system stability margins following considerable contingencies assuming post fault system reaches a steady state. This paper presents a contingency ranking methodology using static security indices to rank credible contingencies considering severity. A Modified IEEE 9 bus system integrating renewables was used to test the approach. The static security indices used independently provides accurate results in identifying severe contingencies but further assessment is needed to provide an accurate picture of static security assessment in an increased time frame of the steady state. The indices driven for static security assessment could accurately capture and rank contingencies with renewable sources but due to intermittency of the renewable source various contingency ranking lists are generated. This implies that using indices in future grids without consideration on intermittent nature of renewables will make it difficult for the grid operator to identify severe contingencies and assist the power system operator to make operational decisions. This makes it necessary to integrate the behaviour of renewables in security indices for practical application in real time security assessment.**

Keywords—Power System Security, Static Security Assessment, Contingency Ranking ,Contingency Selection, Real Power Performance Index, Voltage Performance Index, Renewable technologies

I. INTRODUCTION

To ensure that a power system is operated safely and economically, it is critical for it to be operated securely. In the past, the grid was built and operated by monopolies and the power system was vertically integrated. Planning in vertically integrated power systems ensured that generation and transmission constraints were addressed and were under control with the demand growth. Forecasting the operating conditions of the power system took a simpler approach due to fewer generation and transmission service providers. Disturbances were more predictable making the power system more robust in responding to them. Over the last decade, with the shift to open markets, the possible sources of disturbances have increased. This means the robustness of the power system is reduced hindering its predictability of the operation. The power system itself has become a new competitive environment, and to ensure power system reliability in the long term, power system should be designed to guarantee that power system security and monitoring should be in place to ensure that at all times an adequate security margin is present. Thus, more rigorous safety assessments are required to cater to the new requirements grids have to offer. [1]

To establish whether and at what level a power system is decently safe from unplanned contingencies, it is necessary to carry out accurate Security assessment.[1-2] Security assessment can be carried out as a static and dynamic assessment.

Static Security Assessment (SSA) examines the potential of a power system to resist credible contingencies such as generator outage and line outage by checking limit violations of the post fault power system assuming that it has reached a stable state. The transient and dynamic oscillations due to perturbations in the power system are not accounted for in an SSA. [1]

A power system can be classified into five states. The states are normal, alert, emergency, extreme and restorative state. These states each demonstrate a different level of power system security along with control actions to strengthen power system security. [6]

All the power system constraints are satisfied in the Normal state, that is, the total generation is sufficient to meet the total demand. At this state, there is no overloading of equipment; grid frequency and voltage are maintained within specified limits. The power system will enter an alert state when the level of security goes below an adequate threshold level or if the likelihood of a disturbance happening increases. The constraints would be still satisfied in the alert state, however, considering the reserve capacity there is a possibility that inequality constraints will be violated following some disturbance. In the alert state, if a considerable severe disturbance happens prior to preventive action been taken, the power system will move to the emergency state. The inequality constraints are violated in the emergency state breaching the level of security of the power system. At this state, practically there will be no security level; however, the power system would be still undamaged meaning that control actions can be launched to reinstate the power system back to alert system the least. When the power system is overstressed due to the severity of the disturbance, disintegration of it will be initiated, that is, the power system will enter an extremis state. The power system enters this state if timely emergency actions are not taken or if the emergency actions were not effective. Both equality and inequality constraints are violated and there will be significant portions of loss of system load. To prevent a total collapse of the power system, control action needs to be such that at least certain portions of the power system will be retrieved. When the situation of collapse has been slowed down the power system could enter the restorative state following that certain equipment have restarted or haven't failed and are operating at rated capability. To reconnect disconnected loads control action could be taken. The power system would be capable of now entering back to the alert or normal state. [6]

This paper presents the performance of the static security assessment techniques, namely, active power Performance Index (PI_{MW}) and voltage Performance Index (PI_v) in selecting and ranking contingencies in a power network with renewables. PI_v can accurately identify the contingencies that result in out of limit voltages. PI_{MW} ranks the contingencies based on line overloads.

II. Static Security Performance Indices

Static Security Indices can be determined through various methods. [7]

Active Power performance index (PI_{MW}): The impact that a particular outage would have on the overall power system is quantified through this index.[8] If there is overloading of one or many lines, the value of PI_{MW} will record a larger value and if power flow limits are not exceeded it will provide a smaller value..

Voltage performance index (PI_v): A measure to what extent the voltages deviates from the normal voltage as a result of contingency is measured by this index. If the voltage limits of all bus voltages are maintained, then PI_v value recorded will be small else it will mean that there is a violation of one or many of bus voltages. [8]

Vector voltage performance index (PI_{vv}): In the quantification of PI_{vv}, the voltage limits are defined as two types namely a security limit and alarm limit. The power system will be defined as insecure if PI_{vv} =1 meaning that voltage of busses have exceeded their limits. If the PI_{vv} =0 the power system is said to be in a secure state, that is, bus voltages are within their limits. If the PI_{vv} value is between 1 and 0, the system is said to be in an alarm state. [9] This is a vector performance index so the masking effect will be eliminated in comparison to a scalar performance index. Further, unlike in a scalar performance index where weighting factors will be chosen, this index avoids them.

Composite security index (PI_c): A combination of the active power flow and the voltage indices is represented as PI_c. This index is capable of effectively separating the secure and insecure power system cases. If the PI_c records a value higher than zero and equal to or less than 1, the power system is said to be in an alarm state. When the PI_c records a value of zero, the power system is secure else it is insecure. [10]

Steady state security assessment is conducted by load flow studies in the post-disturbance situation after the power system is assumed to have reached a steady state. Certain outages results in overloading of lines and voltages of busses to be exceeded over their specified limits.

At the load busses, a limit for the voltage constraints will be specified meaning that voltages are expected to be within a higher or lower limit. The higher limit represents the highest secure voltage of the power system that is determined by the maximum voltage. The lower limit represents the voltage below which the power system would not be able to cater the loads. The thermal limits of the transmission lines and concerns on stability will determine the amount of line flows in them. The performance indices are defined such that constraints of the power system, that is, line flows and voltages are treated as soft constraints. That is, any violation of the soft constraints may be tolerated for short period of time thus defined as a penalty function so as to penalize the effect of any severe violation of these constraints. [8]

A. *Active Power Performance Index(PI_{MW})*

The Active Power performance index quantifies the extent lines are overloaded in a given power system.

$$PI_{MW} = \sum_{l=1}^{NL} \left(\frac{W_l}{2n}\right)\left(\frac{P_l}{P_l^{Lim}}\right)^{2n} \tag{1}$$

P_l = The power flow of line *l* in megawatt

P_l^{lim} = The capacity of line *l in* megawatt

n = Specified exponent (n = 1 preferred)

NL = The number of lines

W_l = Real non-negative weighting coefficient

In calculation of PI_{MW}, all line flows are normalized and raised to an even power (n=1, 2…) to avoid absolute magnitude of line flows. A lower value is recorded by the

PI_{MW} index when fewer lines are overloaded and a larger value when the system has overloading of lines. The severity of the overloading of lines is provided by PI_{MW}. [8]

B. Voltage performance index(PI_v)

The deficiency of the reactive power in the system is quantified through the Voltage level performance index. [8]

$$PI_V = \sum_{i=1}^{NB} \left(\frac{W_{vi}}{2n}\right)\left(\frac{(|V_i| - |V_i^{SP}|)}{\Delta V^{lim}}\right)^{2n} \qquad (2)$$

$|V_i|$ =Post contingency voltage value at i^{th} bus

$|V_i^{SP}|$ = Rated voltage value at i^{th} bus

ΔV^{lim} =Voltage deviation limit

n = Exponent of penalty function (n = 1 preferred)

NB =Number of buses

W_{vi} = Real non-negative weighting factor

The threshold above which voltage levels are exceeded is represented by ΔV^{lim}. Contingencies that result in voltage levels falling below this threshold limit will show a larger PI_v value and a lower value when voltage limits are not exceeded. Considering the voltage profile, PI_v is a direct method of contingency ranking and selection based on the severity of contingencies resulting in exceeding bus voltages. [8]

III. TEST CASES

This study is performed on the US Western System Coordinating Council (WSCC) 9 bus system, known as IEEE 9 bus system as shown by Fig.1 [11]. The system modelled in PSCAD in [12] is modified and simulated as two cases, that is, connecting a renewable energy system to the weakest bus in the system and by replacing a synchronous generator with a renewable energy system.

The voltage limits allowable in IEEE 9 bus system are 1.1 p.u. and 0.9 p.u. which gave a ΔV^{lim} of 0.2 used in calculation of voltage performance index.

A modified case of IEEE 9 bus system was created and simulated by adding a Solar Power Plant of 85 MW to the weakest bus of the system identified through load flow study of the base case.

Line outages were simulated in the system by providing a three phase fault followed by line removal through circuit breaker action.

The Active Power Flow performance index and Voltage performance index was calculated and contingencies were ranked based on the two indices separately. The ranking of the contingencies based on the indexes were verified with the test results discussing the suitability of using the indices in accurately ranking contingencies in renewable rich power network.

Each synchronous machine (generator) is represented as a voltage source in the IEEE 9 bus system, and its source impedance is set arbitrarily as 1Ω for simulations. The terminal conditions of each source, with 100MVA base along with the transmission line and load parameters are used for the study. [12]

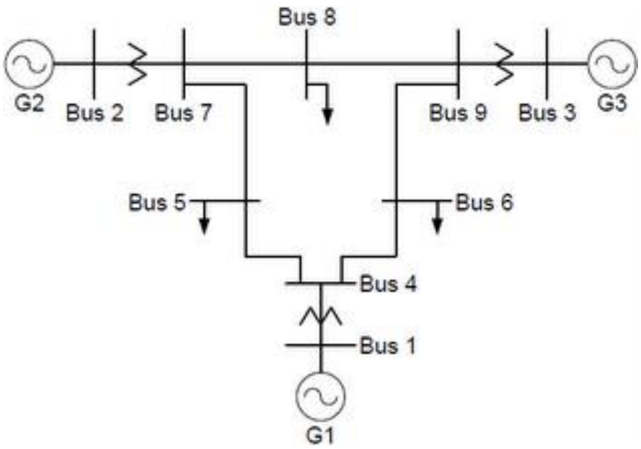

Fig. 1 IEEE 9 bus system [11]

A. Case 1: IEEE 9 bus system

The source and line power flow of IEEE 9 bus system base case is given in Table 1. The Bus voltages of IEEE 9 bus system base case is given in Table 2.

The weakest bus of a power system could be found through the voltage stability margin, that is, lowest voltage stability margin represents the weakest bus. Bus 5 is the weakest bus of the IEEE 9 bus system.[13] Further, load flow studies in this study showed that Bus 5 recorded the lowest voltage.

Table 1: Source and line power flow of IEEE 9 bus system base case

Bus		**P [p.u.]**	**Q [p.u.]**
1		0.7152	0.2761
2		1.632	0.0454
3		0.8512	-0.117
From Bus	**To Bus**	**P [p.u.]**	**Q [p.u.]**
4	5	0.4322	0.2334
4	6	0.283	0.0115
5	7	0.843	-0.1041
6	9	0.634	-0.181
7	8	0.7892	-0.0089
8	9	0.2172	0.0229

Table 2: Bus voltages of IEEE 9 bus system base case

Bus	Voltage (p.u.)
1	1.042
2	1.027
3	1.027
4	1.027
5	1.011
6	1.014
7	1.029
8	1.019
9	1.034

B. Case 2: Modified IEEE 9 bus system with renewables connected to weakest bus

To verify the reliability of using static security indexes in contingency selection and ranking in a bus system modified to integrate renewables, a solar farm of 85 MW was connected with Bus 5 which is the weakest bus.The irradiation was kept at 1000 Wm^{-2} at which the solar farm is delivering a fixed output of 85 MW.

Table 3- Source and line power flow of Modified IEEE 9 bus system with renewables connected to weakest bus

Bus		P [p.u.]	Q [p.u.]
1		0.7163	0.2791
2		1.6300	0.0490
3		0.8500	-0.117
From Bus	**To Bus**	**P [p.u.]**	**Q [p.u.]**
4	5	0.508	0.378
4	6	0.432	--0.02674
5	7	-0.859	--0.1280
6	9	--0.732	-0.2754
7	8	0.956	--0.0238
8	9	0.247	--0.3863

Table 4: Bus voltages of Modified IEEE 9 bus system with renewables connected to weakest bus

Bus	Voltage (p.u)
1	1.040
2	1.025
3	1.025
4	1.025
5	1.009
6	1.010
7	1.027
8	1.017
9	1.032

Table 5: PI_V and PI_{MW} for the Modified IEEE -9 bus system with renewables connected to weakest bus

Tripped line	Case 2: Modified IEEE -9 bus system with renewables connected to weakest bus			
	PI_{MW}	Rank	PI_V	Rank
1-4	2.51	8	15.41	1
4-5	8.41	3	10.40	2
4-6	6.20	5	0.152	9
5-7	7.70	4	9.41	3
6-9	13.49	2	0.46	6
7-2	1.51	9	0.21	8
7-8	20.20.	1	5.89	5
8-9	4.51	6	0.321	7
9-3	3.78	7	8.90	4

The source and line power flow of Modified IEEE 9 bus system with renewables connected to weakest bus is given in Table 3. The Bus voltages of Modified IEEE 9 bus system with renewables is given in Table 4.The PI_V and PI_{MW} for the Modified IEEE 9 bus system with renewables are given in Table 5 along with the rankings of contingencies.

C. Case 3: Modified IEEE 9 bus system by replacing a synchronous generator with renewables

A solar power plant of 85 MW was connected with Bus 3 replacing the synchronous generator with similar capacity. The solar farm is capable of giving 85 MW to the system at an irradiation of 1000 Wm^{-2}.

At a decreased irradiation level of 200 Wm^{-2}, the solar farm is capable of only delivering an output power of 25 MW. The simulation was done with these parameters and ranking was done using the static security indexes where highest severity contingencies were ranked higher on the contingency list.

Table 6: PI_V and PI_{MW} for the Modified IEEE 9 bus system with solar farm operating at high irradiation level (1000 Wm^{-2})

Tripped line	Case 3: Modified IEEE 9 bus system by replacing a synchronous generator with renewables			
	PI_{MW}	Rank	PI_V	Rank
1-4	1.45	9	21.76	1
4-5	2.96	8	11.21	2
4-6	4.78	5	4.90	5
5-7	8.56	4	0.25	9
6-9	15.89	2	1.46	8
7-2	20.39	1	9.82	3
7-8	13.21	3	2.41	7
8-9	4.67	6	7.80	4
9-3	3.95	7	4.27	6

Table 7: PI_V and PI_{MW} for the Modified IEEE 9 bus system with solar farm operating at low irradiation level (200 Wm^{-2})

Tripped line	**Case 3: Modified IEEE -9 bus system by replacing a synchronous generator with renewables**			
	PI_{MW}	**Rank**	**PI_V**	**Rank**
1-4	0.46	8	5.40	7
4-5	5.41	6	7.60	5
4-6	3.11	7	14.78	2
5-7	8.92	4	12.98	3
6-9	7.46	5	18.14	1
7-2	0.28	9	3.50	8
7-8	13.61	2	2.10	9
8-9	20.81	1	7.51	6
9-3	10.21	3	8.90	4

It is evident from Table 6 and Table 7 that two lists of contingency ranking is generated for the same system due to intermittency of renewables.

IV. ACCURANCY OF RANKING BY PERFORMANCE INDICES

It is evident from Table 5 that the outage of line 7-8 is ranked 1 and is the most severe contingency in terms of line overloading in Case 2 where a solar plant delivering 85 MW was connected to the weakest bus of the system.

Verification on the selection of the most severe contingency based on PI_{MW} was done by analyzing the post contingency power of the rank 1 and rank 2 contingencies as shown in Table 8.

It is evident from Table 8 that for outage 7-8, the heavily overloaded line out of all lines is 5-7 which is overloaded by 0.426 p.u. and for outage 6-9, line 5-7 is overloaded by 0.39 p.u.

Table 8: Post contingency power flows of Case 2

Line	**Post contingency power (p.u.)**	**Post contingency power (p.u.)**	**Maximum Power (p.u.)**
	Outage of 7-8 line	**Outage of 6-9 line**	
1 -4	0.7321	0.795	0.7152
4-5	0.288	0..14	0.4322
4 6	0.9956	0.128	0.283
5 -7	1.269	1.231	0.843
6-9	0.0436	0	0.643
7 -2	1.34	1.62	1.632
7-8	0	0.41	0.7892
8-9	0.890	0.75	0.2172
9-3	1.187	0.845	0.8512

Table 9: Post contingency voltages of Case 2

Line	**Outage of line 1-4**	**Outage of line 4-5**	**Pre Contingency voltage (p.u.)**
	Post contingency voltage (p.u.)	**Post contingency voltage (p.u.)**	
1	1.028	0.8932	1.052
2	0.8011	0.9130	1.041
3	0.7713	0.9581	1.04
4	0.6860	0.7840	1.036
5	0.678	0.7712	1.008
6	0.6741	0.351	1.025
7	0.856	0.942	1.041
8	0.7321	0.920	1.032
9	0.786	0.9741	1.047

In terms of V_{PIV}, the rank 1 and rank 2 severe contingencies leading to over voltages are due to outage of line 1-4 and 4-5 respectively as evident from Table 5. Verification of the ranking based on the test results in Table 9 shows that the outage of line 1-4 creates voltage deviation from the limits on all busses except bus 1. However, outage of 4-5 leads to voltage limit violation on busses 4, 5, and 6 only.

The results in Table 8 and Table 9 provide verification of the accuracy of the ranking done based on PI_{MW} and PI_V as shown by Table 5.

V. CONCLUSION

The main thought behind contingency screening is to identify severe contingencies accurately from a set of large contingencies and doing so will reduce computational time of performing security assessment. This study shows that contingency selection and ranking based on independent performance indexes provide accurate results in identifying severe contingencies in a post fault stable system; however, further assessment is needed to provide an accurate picture of static security assessment with increased time frame. That is, a contingency that is identified as the most severe considering the highest number of overloaded buses may not be that severe due to increased tripping time of the overloaded buses. However, on the other hand, a contingency identified as less severe with less overloaded buses may cause tripping of the overloaded buses within short time duration. A composite index would be more suitable to assess power system security, meaning contingencies will be ranked after considering the behaviour of the system to changes in different system parameters rather than an independent parameter.

In renewable rich networks, due to the intermittent nature of renewable sources, the vulnerability of the grid changes with time and power system security done using the active power index and voltage power index provides different sets of contingency ranking at different irradiation levels. This is misleading information to the operator if the system fails at a time when irradiation is lower while the contingency list is created at a time when renewable generation was the highest. Thus, there is a requirement that a novel performance index incorporating changes in solar ramp rates may be derived so the operator can take more proactive decisions in future grids. These indexes can then be used in contingency ranking and selecting in real time algorithms implemented to decrease the computational time and could be used to provide accurate results on renewable rich networks.

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