A STRATEGY TO IDENTIFY CONGESTIONS OF TRANSMISSION NETWORKS IN N-1 CONTINGENCY: KHANH HOA CASE STUDY

CHIẾN LƯỢC XÁC ĐỊNH TẮC NGHẼN LƯỚI TRUYỀN TẢI TRONG TRƯỜNG HỢP SỰ CỐ N-1: LƯỚI ĐIỆN TỈNH KHÁNH HÒA

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Abstract - Today, with the high penetration of renewable, ensuring the safety of the system is one of the major cases in electrical system operation, thus the operator must evaluate the sensitivity analysis of the network in N-1 contingencies to be aware of the situation of the network in any failure events. In this paper, two major factors that impact the safety of the system are considered. They are the substitution of injecting power at a bus and the line outage. The paper implements a model based on these two factors to quickly identify congestions in post-contingency relating to losing a generator considered as a sudden change of a large amount of renewable energy or opening of a transmission line. Eventually, the model is tested with the 110kV transmission network of Khanh Hoa Province to identify sensitivity elements of the network which need to be considered in stability or reliability analysis.

Key words - Generation Shift Factors; Line Outage Distribution Factors; renewable energy; post-contingency; sensitivity analysis

Tóm tắt - Ngày nay, nguồn năng lượng tái tạo đang thâm nhập ngày càng nhiều dẫn đến tiêu chí độ tin cậy trở thành yếu tố rất quan trọng trong việc vận hành hệ thống. Do đó, các nhà vận hành hệ thống phải đánh giá độ nhạy của hệ thống trong trường hợp sự cố N-1 nhằm đảm bảo hệ thống làm việc an toàn trong các trường hợp sự cố. Trong bài báo này, hai chỉ số quan trọng, đại diện cho công suất phát và tình trạng làm việc của đường dây, thường được sử dụng để đánh giá độ làm việc an toàn của hệ thống được thảo luận. Bài báo phát triển mô hình toán dựa trên hai chỉ số này nhằm xác định nhanh chóng các trường hợp sự cố lớn khi thay đổi công suất phát do yếu tố bất định của năng lượng tái tạo hoặc cắt đường dây truyền tải đột ngột. Cuối cùng, mô hình đề xuất được kiểm nghiệm với lưới điện truyền tải 110kV tỉnh Khánh Hòa nhằm xác định các yếu tố dễ bị sự cố của lưới điện gây ảnh hưởng đến độ ổn định và độ tin cậy của hệ thống.

Từ khóa - Chỉ số thay đổi công suất phát; chỉ số mất đường dây; năng lượng tái tạo; chế độ làm việc sau sự cố; phân tích độ nhạy

1. Introduction

A power system is formed of complicated devices taking part in the operation. Besides optimizing power flow to provide demands with the lowest cost, security is one of the most important factors in power system operation. Today, the dispatched generators are mostly decided in the day-ahead market which aims to clear the market one day before the dispatching day, thus the sensitivity analysis of a transmission line is one of the major tasks of the dispatch-center to make sure that the system is safe during any fault events. In Vietnam, today, there are many publications that enhance the stability of the network. Paper [1] shows some locations where there is a low voltage issue happening in some situations, i.e., holiday, raining season or sunny season, proposed a method to increase the voltage stability. Papers [2, 3] using wind generators to support the voltage stability to enhance the safety of the system in any contingencies. However, the sensitivity analysis of the network is not considered enough since it has an important impact on the safety of the network.

In a normal operation, the balance of the system is always guaranteed to satisfy demand and the transmission capacity is also sufficient to transfer energy from sources to demand. If the system continues to operate without any unexpected power outages or the normal operating states of all the components are stable, then it means the network is without any reliability issues. However, when there is an unexpected incident, the negative impact on an element of the electricity system may affect the reliability of the entire system. This factor may cause lightning strikes to the line, short circuit, equipment damage or technical error from the operator.

There are many factors which impact the safety of the network. It can come from nature elements such as the sudden temperature rising, humidity changing, etc. Or maybe from mistakes in operating processes, the high demand increase, etc. All the causes above can bring bad consequences to the operating system and reduce the reliability of the network. System security involves practices designed to keep the system operating when contingencies occur. Therefore, many researches have been done and articles have shown solutions to deal with these problems: the paper [4] reviews the status of security analyses in vertically integrated utilities and discusses the impact of system security on the operation and the planning, the model of contingency analysis was formulated and was used to calculate in the papers [5, 6] used contingency analysis to detect weaknesses in the power system, the paper [7] brings us the overall visions about power system security, etc. Meanwhile, this paper presents a simple strategic to evaluate the security of the system by using sensitivity factors in cases of unpredictable of renewable energy, failures of the transmission network. In which, two important factors will be analyzed and calculated namely: Generation Shift

Factors (GSF) and Line Outage Distribution Factors (LODF). Then a proposed algorithm developed based on these two components to identify the potential congestions of the system. The proposed algorithm can be applied into two tasks: (i) network planning [8-11] and (ii) optimize transmission switching [12, 13]. The model will evaluate the power flow of all lines for pre-contingency and post-contingency, then detecting which lines have potential risk to the network in N-1 contingencies.

The paper is organized as follows: Section II will introduce sensitivity factors and present the formulation of Generation Shift Factors (GSF) and Line Outage Distribution Factors (LODF) for the security problems. The results of the Khanh Hoa case study will be shown and discussed in Section III from using the new equations on the popular test case [14].

2. Sensitivity factors

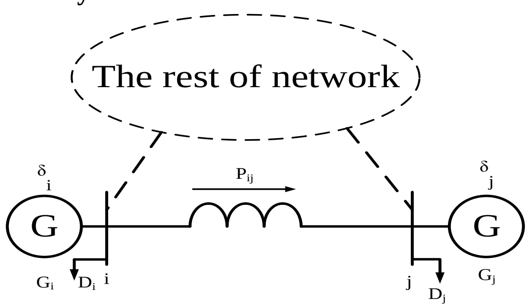

Figure 1. *A simple network*

In this section, the paper uses a very simple network to illustrate the methodology in Figure 1. Here, two nodes i and j including two generators (g_i and g_j) and two load (d_i and d_j) and connected by the line ij. Then, they relate to the rest of the network including many lines, generators, and loads.

2.1. Mathematical model

From (1)-(4), the mathematical model of DC-OPF is displayed [15]. The objective (1) is the minimization of generation cost:

$$MinOF \sum_{g_1,g_2} a_g.\left(P_g\right)^2 + b_g.p_g + c_g \quad (1)$$

Eqs (2)-(4) present the network constraints. Here, (2) presents power flow of the line ij, (3) guaranties the balance power at each node, and (4) presents the limitation of transfer capacity of the line ij. Finally, the angle of slack bus (i) is fixed to zero (5).

$$\text{St:} \quad P_{ij} = \frac{\delta_i - \delta_j}{x_{ij}{}^2} \quad \forall l \in L \quad (2)$$

$$P_g^i - P_d^i - P_{ij} + P_{ji} = 0 \quad \forall i \quad (3)$$

$$-P_{ij}^{max} \leq P_{ij} \leq P_{ij}^{max} \quad \forall l \in L \quad (4)$$

$$\partial^{slack} = 0 \quad (5)$$

Where $g \in G$ is generator and $d \in D$ is demand, and i, j are nodes between line $l \in L$. a_g, b_g, c_g are parameters in cost function of generator.

Because of using DC-OPF model, some assumptions are adopted: (i) Only consider active power flow; (ii) the branch impedance is equal to the reactance only; (iii) all voltage magnitudes are equal to 1 p.u; (iv) voltage angles are close to each other, so $\sin(\delta_i - \delta_j) = \delta_i - \delta_j$.

The general equation of D-factors:

$$D = \frac{\Delta f_{ij}}{\Delta P} \quad (5)$$

where Δf_{ij} is the variation in MW of power flow on line ij after a contingency happens, and ΔP is the variation in MW of power flow of failure events (power of generator or demand suddenly increase or decrease).

The post-contingency power flow at line ij is then calculated by the power flow at pre-contigency plus with the deviation of power flow:

$$P_{ij}^{post} = P_{ij}^{pre} + D.\Delta P \quad (6)$$

2.2. Generation Shift Factors

GSF are formulated based on the failure event which is the power change at a bus. This change can be the unpredictable of renewable energy.

The generation shift factor of the flow in line ij of power change in bus m (ΔP_m) is obtained as follow [8]:

$$GSF = \frac{\Delta f_{ij}}{\Delta P_m} = \frac{X_{im}}{X_{jm}} \quad (7)$$

Using the equation (2), the line flows are calculated in post-contingency period:

$$P_{ij}^{post} = P_{ij}^{pre} + GFS.\Delta P_m \quad (8)$$

If the generator reduces its power by P_g^m, then the equation (2) will be represented by:

$$P_{ij}^{post} = P_{ij}^{pre} + GFS.(-\Delta P_g^m) \quad (9)$$

If the generator reduces its power by P_g^m, then the formula (2) will be represented by:

$$P_{ij}^{post} = P_{ij}^{pre} + GFS.\Delta P_g^m \quad (10)$$

After the post-contingency power flow of all branches are obtained, they are compared to its limit and those exceeding their limitation are warned to the operator. It would tell the operator that the loss of generation at bus m would result in an overload on the line ij.

2.3. Line Outage Distribution Factors

The LODFs are used in a similar manner, they are applied to analyze the influences of the line outage on the rest of the network. In this case, if all the power of the line ij (the line outage) will be absorbed by line nm. Now using (5), LODF is calculated using the following (9):

$$LODF = \frac{\Delta f_{nm}}{\Delta P_{ij}} = \frac{X_{in} - X_{im} - X_{jm} + X_{jm}}{X_{ij}(1 - \frac{X_{nn} + X_{mm} - 2X_{nm}}{X_{mn}})} \quad (11)$$

where ΔP_{ij}^{pre} is the pre-contingency power flow of line ij before it was outages.

Then the post-contingency line flow of line nm with line ij out can be determined:

$$P_{nm}^{post} = P_{nm}^{pre} + LODF.P_{ij}^{pre} \quad (12)$$

Using LODF, the operator can test all the lines in the network for overload when a certain line is disconnected. The overload reports will be sent to the operations personnel in the form of alarm message.

The sensitivity factors which formulated above have the interesting features as following:

• The procedure of calculating these factors does not involve any optimizations;

• These factors are calculated in advance and apply them in real-time applications;

• These factors only depend on network topology, therefore, if the topology is changed, GSF and LODF are recalculated;

• To calculate GSF, assuming that the changes at any bus are quickly compensated by reference bus.

3. Proposed Algorithm

In order to simulate the sensitivity analysis of the network, the paper developed an algorithm in Figure 2 according to two major factors mentioned above. The algorithm includes two main parts: (i) GSFs analysis and (ii) LODFs analysis. The first part focuses on the change in power at bus and the second part is for the losses of one transmission line in the network. It should be noted that GSFs and LODFs of the network are calculated in advance. Here, i is for bus and k is for the line. It should be noted that the DC-OPF is solved in advance to obtain P_{ij}^{pre}.

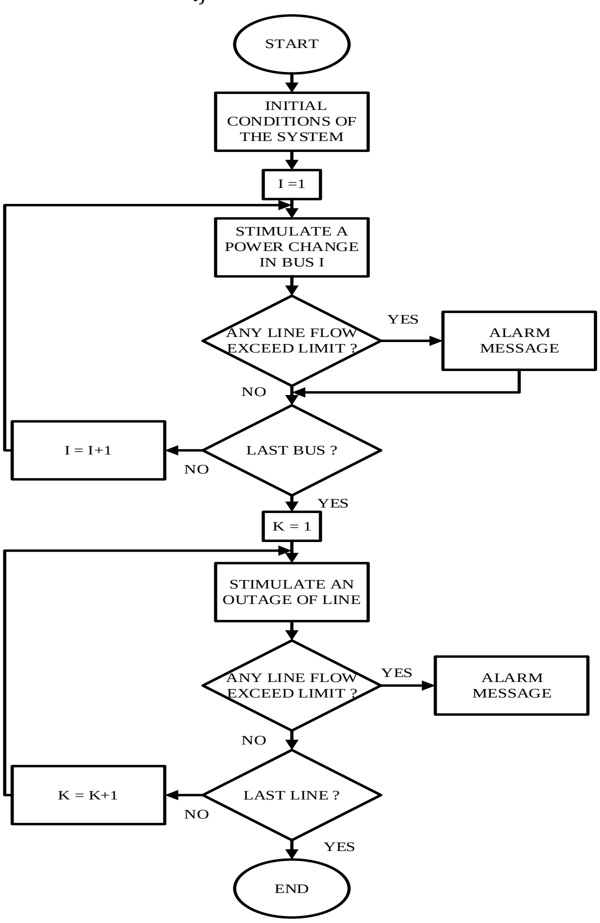

Figure 2. *Full security analysis procedure*

For each criterion, the evaluation contains three main steps:

• **Step 1**: Change power in bus i for the first part or open line k for the second part.

• **Step 2**: Using P_{ij}^{pre}, GSFs or LODFs corresponding to bus i and line k to check the capacity limit of each line.

• **Step 3**: If the line limit is exceeding, the alarm message is sent to the operator. Otherwise, the next bus i or line k is evaluated and it goes back to Step 2.

The algorithm stops when all buses and lines are evaluated.

4. Simulation and results

The mathematical model was developed entirely on the version of GAMS for research community [14] based on the algorithm in Figure 1. Then the paper uses the 110kV transmission network in Khanh Hoa Province to test the proposed model regarding several cases. Finally, the robustness of the proposed model is checked with the commercial software PSS/E [16].

4.1. Khanh Hoa Province electricity network

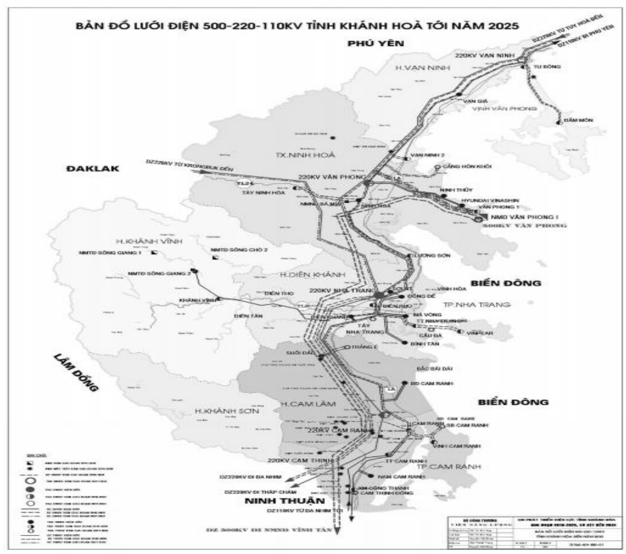

Figure 3. *The topology of Khanh Hoa province in 2025 [17]*

The topology of Khanh Hoa Province is presented in Figure 3 including four demand zones with the consumption in Table 1. There are six solar power plants operating with 223 MW, and many are planning to operate in 2025. The topology of Khanh Hoa Province contains 500 kV, 220 kV, and 110 kV. This paper only considers the 110 kV voltage level.

Table 1. *The consumption of four demand zones until 2035 (unit: MW) [17]*

Zone	2025	2030	2035
Zone 1	245	372	539
Zone 2	464	667	949
Zone 3	235	356	516
Pmax	910	1380	1980

Aiming to evaluate the proposed model, the paper creates four scenarios presenting different operating modes of the system in 2022 and 2025:

- Scenario 1: 70% capacity of generators and 100% demand;
- Scenario 2: 100% capacity of generators and 70% demand;
- Scenario 3: 70% capacity of generators and 70% demand;
- Scenario 4: 100% capacity of generators and 100% demand.

The selected elements to evaluate the reliability of the Khanh Hoa power system must follow the criteria: (i) High load; (ii) high sensitivity factors; (iii) are able to modify power (GSHF) and the trip transmission carrying a high load; (iv) the direction of sensitivity factors is the same with power flow.

4.2. Results

4.2.1. Generation Shift Factors

After running the proposed model, the highest GSHF of some elements are shown in Table 2 and 4 for 2022 and 2025, respectively. The first column of Table 2 and 4 present the GSHF of transmission lines with respect to the buses from column 2 to column 6. Power flows are calculated based on GSHF then comparing to the maximum transfer capacity of transmission line showed in Table 3 and 5 for four scenarios in 2022 and 2025, respectively. The first column of Table 3 and 5 present the transmission lines, meanwhile the second to the sixth column shows the scenario.

Table 2. *The highest GSHF of some elements of the network in 2022*

GSHF		Van_Phong	Van_Ninh	Vinh_Cam_Ranh	TBA_110_Van_Phong	Van_Phong
ĐMT_sim_HADO	Ninh_Hoa	0.88				
Van_Phong	Van_Ninh		-0.8			
Vinh_Cam_Ranh	TBA_220_Cam_Ranh			0.77		
Nha_may_loc_dau	Van_Phong				-0.7	
DMT_Ninh_Tan	Nha_Trang					0.74

Table 3. *The comparison between power flow and maximum capacity in percentage in 2022*

Power flow		SC1	SC2	SC3	SC4
ĐMT_sim_HADO	Ninh_Hoa	47	31	31	46
Van_Phong	Van_Ninh	48	43	38	55
Vinh_Cam_Ranh	TBA_220_Cam_Ranh	22	17	16	23
Nha_may_loc_dau	Van_Phong	67	37	41	60
DMT_Ninh_Tan	Nha_Trang	9	7	7	9

From Table 2 and 3, the line **Nha_may_loc_dau-Van_Phong** carries more than 50% of capacity in four scenarios (67% in **SC1**). The GSHF of **TBA_110_Van_Phong** respect to the transmission line **Nha_may_loc_dau-Van_Phong** is high (0.7). **TBA_110_Van_Phong** is PQ bus, thus it can increase or decrease the consumption. To sum up, the line **Nha_may_loc_dau-Van_Phong** is selected for further analysis in 2022 in case **TBA_110_Van_Phong** suddenly changes consumption.

Table 4. *The GSHF of some elements of the network in 2025*

GSHF		DMT_Kieu_Thi	Vinh_Cam_Ranh	Trung_tam_Nha_Trang	DMT_Ninh_Sim	DMT_Hoa_Son
TBA_110_Cam_Ranh	TBA_220_Cam_Ranh	0.83				
Vinh_Cam_Ranh	TBA_220_Cam_Ranh		0.8			
Trung_tam_Nha_Trang	Ma_Vong			0.9		
DMT_Ninh_Sim	Ninh_Hoa				0.89	
Van_Ninh	Van_Gia					-0.67

Table 5. *The comparison between power flow and maximum capacity in percentage in 2025*

Power flow		SC1	SC2	SC3	SC4
TBA_110_Cam_Ranh	TBA_220_Cam_Ranh	80.5	100.5	77.3	104
Vinh_Cam_Ranh	TBA_220_Cam_Ranh	70	60	53	76
Trung_tam_Nha_Trang	Ma_Vong	27	13	16	23
DMT_Ninh_Sim	Ninh_Hoa	24	41	27	38
Van_Ninh	Van_Gia	30	6	20.2	9

From Table 4 and 5, the line **TBA_110_Cam_Ranh-TBA_220_Cam_Ranh** uses to overload. The GSHF of **DMT_Kieu_Thi** respects to the transmission line **TBA_110_Cam_Ranh-TBA-220_Cam_Ranh** is quite high (0.8325). **DMT_KIEU_THI** is the PV bus; thus, it can increase or decrease power. Therefore, in 2025, the GSHF of the transmission line **TBA_110_Cam_Ranh-TBA-220_Cam_Ranh** in **SC 3** is selected to investigate in case **DMT_Kieu_Thi** suddenly changes power.

4.2.2. Line Outage Distribution Factors

Table 6. *The LODF of some elements of the network in 2022*

LODF	Nha_Trang – Dien_Khanh	Vinpearl – Cau_Da	Khanh_Vinh – Dien_Khanh	Van_Phong – Luong_Son	Nha_Trang – Dong_De
Van_Phong – Ninh_Hoa				0.29	
Dien_Phu – Dien_Khanh	0.77				
Dong_De – Ma_Vong		-0.44			
TT_Nha_Trang - Vinpearl			-0.56		
Det_Nha_Trang – Nha-Trang					-0.61

The paper repeats the same procedure of GSHF for LODF, the highest LODF of some elements are shown in Table 6 and 8 for 2022 and 2025, respectively. The first column shows the transmission line which has the highest LODF with respect to the considered line in the first row, i.e., the considered line is Nha_Trang –

Dien_Khanh, the highest LODF is Dien_Phu – Dien_Khanh (0.77). Power flows are calculated based on LODF then comparing to the maximum transfer capacity of transmission line showed in Table 7 and 9 for four scenarios in 2022 and 2025, respectively. The first column presents the effected and opened elements in which the opened element will change the power flow on the affected element.

Table 7. *The comparison between power flow and maximum capacity in percentage in 2022*

Power flow			SC1	SC2	SC3	SC4
Affect	Dien_Phu	Dien_Khanh	13	7	3	3
Open	Van_Phong	Luong_Son	39	25	26	38
Affect	Van_Phong	Ninh_Hoa	46.5	31	31	46
Open	Nha_Trang	Dien_Khanh	20	2	6.9	11
Affect	Dong_De	Ma_Vong	20	6	10	16
Open	Vinpearl	Cau_Da	61	53	47	66
Affect	TT_Nha_ Trang	Vinpearl	54	50	43	59
Open	Khanh_Vinh	Dien_Khanh	5.8	11.6	6.8	9.6
Affect	Det_Nha_ Trang	Nha_Trang	33	19	21	32
Open	Nha_Trang	Dong_De	34	19	22	32

From Table 6 and 7, the power flow on lines is low (less than 70% of the maximum capacity). The LODF of the line **Det_Nha_Trang – Nha_Trang** affected by the line **Nha_Trang – Dong_De** in **SC1** is quite high (-0.61), meanwhile the power flow is medium but enough for further investigation. Therefore, in 2022, the paper selects the line **Det_Nha_Trang – Nha_Trang** in **SC1** to investigate in case the line **Nha_Trang – Dong_De** is opened while transferring a high power.

From Table 8 and 9, some transmission lines are highload or overload, i.e. **TBA_110_Cam_Ranh – TBA_220_Cam_Ranh** in 4 SC. In SC2, the LODF of **Nha_Trang – Dien_Phu** and **Nha_Trang – Dien_Khanh** is quite high (0.7686). Therefore in 2025, the paper selects the line **TBA_110_Cam_Ranh – TBA_220_Cam_Ranh** in SC4 and the line **Nha_Trang – Dien_Phu** when open the line **Nha_Trang – Dien_Khanh** in SC2 to investigate.

Table 8. *The LODF of some elements of the network in 2025*

LODF	Nha_ Trang – Dien_Khanh	Vinpearl – Cau_Da	Khanh_ Vinh – Dien_Khanh	Van_ Phong – Luong_Son	Nha_ Trang – Dong_De
Nha_Trang _ Dien_Phu	0.77				
Nha_Trang – Dong_De		0.4			
TT_Nha_ Trang - Vinpearl			-0.19		
TBA_110_ Cam_Ranh – TBA_220_ Cam_Ranh				0.16	
Van_Phong – Ninh_Hoa					-0.53

Table 9. *The comparison between power flow and maximum capacity in percentage in 2025*

Power flow			SC1	SC2	SC3	SC4
Affect	Nha_Trang	Dien_Phu	25	75	43	59
Open	Nha_Trang	Dien_Khanh	1	36	15	21
Affect	Nha_Trang	Dong_De	42	18	25	35
Open	Nha_Trang	Ma_Vong	66	31	40	58
Affect	TT_Nha_ Trang	Vinpearl	56	42	40	58
Open	TBA_220_ Cam_Ranh	Ma_Vong	33	19	21	30
Affect	TBA_110_ Cam_Ranh	TBA_220_ Cam_Ranh	80.5	100.5	77.3	104
Open	Vinh_CR	CR220	70	60	53	76
Affect	Van_Phong	Ninh_Hoa	10	36	14	21
Open	Ninh_Hoa	Luong_Son	21	29	20	29

To sum up, the transmission lines and scenario selected to investigate are presented in Table 10. Here, the first column presents the considered year (2022 or 2025). The second and fifth column present the selected line while the third and sixth columns show the considered bus which can suddenly increase or decrease power. The rest of the columns show the scenario.

Table 10. *The synthetic of selected lines and scenarios for analysis*

	GSHF			LODF		
	Line	**Bus**	**SC**	**Line**	**Bus**	**SC**
2022	Nha_may_l oc_dau- Van_Phong	TBA_11 0_Van_P hong	1	Det_Nha_ Trang – Nha_Trang	Nha_Trang – Dong_De	1
2025	CR110_CR 220	DMT_Ki eu_Thi	3	CR110_CR 220	Vinh_CR – CR_220	2
				Nha_Trang – Dien_Phu	Nha_Trang – Dien_Khanh	4

Table 11. *The synthetic of selected lines and scenarios for analysis*

Line	**GSHF**			**LODF**		
	Pre-contingency (MW)	**Post-contingency (MW)**		**Pre-contingency (MW)**	**Post-contingency (MW)**	
		Proposed model (MW)	**PSS/E**		**Proposed model (MW)**	**PSS/E**
Nha_may_ loc_dau- Van_Phong	58.3	42.7	42.7			
CR110_ CR220	145.8	158.2	158.3			
Det_Nha_ Trang – Nha_Trang				-30.6	-59.83	-59.9
CR110_ CR220				208.3	196.49	196.4
Nha_Trang – Dien_Phu				-73.3	-100.278	-100.3

The paper uses the proposed model to calculate the power flow of selected lines in the post-contingency. The result is checked with the commercial software PSS/E to confirm the ability of real application of the proposed model, show in Table 11. The first column presents the selected line. The second and fifth columns present the power flow of lines in the pre-contingency. The rest of the columns show the power flow in the post-contingency.

The result shows that the difference of power flow between the proposed model and the commercial software is very low (less than 0.2%). This can confirm the accuracy of the model.

5. Conclusion

This paper presents an algorithm to calculate factors to analyse contingency in power system. The GSHF can determine the element affected the most in case the power suddenly changes. Meanwhile, the LODF can find the element affected the most in case opening a certain line. With the results, it is possible to obtain from realistic testing case of Khanh Hoa, it shows a lot of potential applications in practical works. The proposed model can determine the most effective element when uncertainty factors occur, especially the high penetration of renewable energy in a short time.

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