UDC 621.3 https://doi.org/10.20998/2074-272X.2023.1.10

P. Venkatesh, N. Visali

Investigations on hybrid line stability ranking index with polynomial load modeling for power system security

Introduction. *In recent years, numerous non-renewable and renewable energies are connected to the grid to meet the demand. Also, transient variation with loads poses the shortcomings for generating units, transmission and distribution networks. In this regard, the study on choice of suitable load modelling is essential to predict the system characteristics. The aspect of the research design is a ZIP load model, which, when combined with contingency criteria and constant-impedance, constant-current, and constant-power loads, produces realistic and long-term load representations.* ***Purpose.*** *The proposed technique, infers the single transmission line outage for obtaining the contingency ranking to ensure the system behavior.* ***Methods.*** *The proposed mathematical model with hybrid line stability ranking index has been used for observing the stability analysis with and without considering unified power flow controller.* ***Results****. The power system involves many unpredictable conditions or contingency conditions like single transmission line outage, double transmission line outage, generator outage and load variations. This paper mainly focuses on the single transmission line outage for obtaining the contingency ranking.* ***Practical value.*** *The recommended stability analysis has been very beneficial in establishing a secure transmission power system.* References 19, tables 8, figures 3.

Key words: **hybrid line stability ranking index, power system security, unified power flow controller.**

Вступ*. Останніми роками для задоволення попиту до мережі підключається безліч невідновлюваних і відновлюваних джерел енергії. Крім того, перехідна зміна навантаження створює недоліки для генеруючих установок, передаючих та розподільчих мереж. У зв'язку з цим дослідження з метою вибору відповідного моделювання навантаження має важливе значення для прогнозування характеристик системи. Одним із аспектів побудови дослідження є модель навантаження ZIP, яка у поєднанні з критеріями непередбачених обставин та навантаженнями з постійним імпедансом, постійним струмом та постійною потужністю дає реалістичні та довгострокові уявлення навантаження.* ***Мета****. Пропонований метод передбачає відмову однієї лінії передачі для отримання рейтингу непередбачених обставин для забезпечення поведінки системи.* ***Методи****. Запропонована математична модель із рейтинговим індексом стійкості гібридної лінії використовувалася для спостереження за аналізом стійкості з урахуванням та без урахування уніфікованого контролера перетікання потужності.* ***Результати****. Енергосистема включає безліч непередбачуваних умов або непередбачених обставин, таких як відключення однієї лінії передачі, відключення подвійної лінії передачі, відключення генератора і коливання навантаження. Ця робота присвячена відключенню однієї лінії електропередачі для отримання рейтингу непередбачених обставин.* ***Практична цінність****. Рекомендований аналіз стабільності виявився дуже корисним під час створення надійної системи передачі електроенергії.* Бібл. 19, табл. 8, рис. 3.

Ключові слова: **індекс стійкості гібридної лінії, безпека енергосистеми, єдиний контролер потоку потужності.**

1. Introduction. Multilevel electricity is necessity of the maximum elementary condition of the contemporary world. Hence, safeguarding the safety of the power system is identical important. The major goal of power system security is to deliver consistent power to the clients short of disruption, harm to the user utilizations, and financial process of the power system. But such a power system is also disposed to numerous problems like the transmission line outage, the generator outage, the rapid increase in load demand, the loss of a transformer, etc. which are known as contingencies. Power system safety is one of the keys stimulating errands in the power system. The gears of blackouts due to contingency in the power system are fetching extra frequent in new times. It causes substantial losses to the industries and gravely disturbs the daily life of a common man. Thus, it is significant to accept a precise and active measure to stop the propagation of contingency to other lines which is the major cause of the blackout. Contingency analysis is used for fast guessing the system stability right after the outage or any abnormal conditions. The purpose of the contingency plan is to ascertain the change within the device's functioning, which can occur after the fault element is removed. Large violations inline flow may end in single line outages which may cause cascading effects of the outages and may also cause overloading on the other lines. If such overload results from a line outage there's an immediate essential for the regulator action to be taken. Therefore, contingency analysis is one of the prime important tasks to be met by the power system planners and operation engineers. Several steady-state and dynamic contingency ranking methods are used for contingency screening [1, 2].

Load models may be used to predict how loads will respond to changes in voltage or frequency. It's important to choose a load model that is easy to understand and can appropriately represent a variety of load response situations while executing. In this study, the effects of steady-state and polynomial load models are examined. This model is less precise than the polynomial load model because it depicts a combination of three different sorts of features in a single load. It is possible to express resistive loads, induction motor loads, and variable-frequency loads in a polynomial load model by using the constant impedance, the constant current, and the constant power. As a result, the polynomial load model is more accurate since it accurately depicts load [3].

During any disturbances in the system, the stability of the system becomes vulnerable and there is a high risk of moving towards global instability or total collapse, or even blackout if preventive actions are not taken quickly. When installed and calibrated properly, flexible AC transmission system (FACTS) devices may alleviate several power system problems including contingency. FACTS devices have shown good performance in solving the contingency issues of the power systems. An index-based strategy for placing FACTS devices is found to be extremely precise and computationally efficient. Static and dynamic analyses of the system are both possible using this tool. The two most affected parameters due to contingency in a transmission system are line loading and voltage stability. The line overload index and voltage stability index must be combined to estimate system stress under emergency situations. Line stability index is easier to calculate, takes less time, and can identify weak buses [4, 5].

Unified power flow controller (UPFC) is the most adaptable and versatile FACTS device [6, 7] due to its use of both series and parallel inverters connected by a shared DC connection. FACTS devices are placed on the most severe line to reduce the severity of the line. A hybrid stability ranking index has been used for contingency ranking. The position of the UPFC is recommended to be on the line with the greatest chance of severity. UPFC is tuned for providing compensation [8]. The proposed method is implemented and tested on IEEE 14 and IEEE 118 bus system.

In this paper, section 1 briefs the polynomial load model or ZIP (constant impedance *Z*, constant current *I*, constant active power *P*) modelling and other existing modeling. Section 2 gives an overview of the contingency ranking approach and represents the contingency ranking process in a flowchart. Section 3 gives an overview of the steady-state and polynomial load model used to analyse the contingency. The developed mathematical model incorporated with Newton-Raphson method is used for analysing the stability of the system. Section 4 explains a hybrid line stability index, which is used to assess the stability of the lines between two buses. According to the value of this index the lines which are under stressed conditions can be identified. Section 5 explains the algorithm used for ranking the contingency in the power system is explained. Section 6 gives an overview of the UPFC. It is placed in the most severe line and simulated to provide compensation. Section 7 shows the results obtained for load modelling and then the results obtained while performing single line outages are shown. From these results, the most critical lines are identified and compensated. The results obtained before compensation and after compensation are compared and section 8 reviews the complete effort done and concludes the study. It clarifies the robustness and usefulness of the slants accessible in this paper.

2. Contingency ranking approach. Contingency analysis is a fit know function in modern energy management systems. Contingency analysis of system may be a main movement in power grid planning and process. Generally, an outage of single line or transformer may lead to overloads in other branches and also cause sudden system voltage rise or drop [9]. The power system security can be analyzed by ranking the contingencies based on the severity of the contingency. It consists of three basic steps to make the analysis easier [10, 11]. The three steps are contingency creation, contingency selection, and contingency evaluation.

Contingency creation.

It involves of all set of likely contingencies that may arise in a power system. This step consists of generating contingency lists.

Contingency selection.

In this step severe contingencies are selected from the list that leads to the bus voltage and power edge ruins. Least severe contingencies are eliminated to minimize the contingency list. It uses line stability index to find the sternness of contingencies.

Contingency evaluation.

It is the utmost weighty step which embraces essential control and safety actions in order to lessen the effect of contingency. There are various types of contingencies such as line outage, bus outage and transformer outage. Line outage is analyzed in this paper as it is the most occurred contingency in the system (Fig. 1).

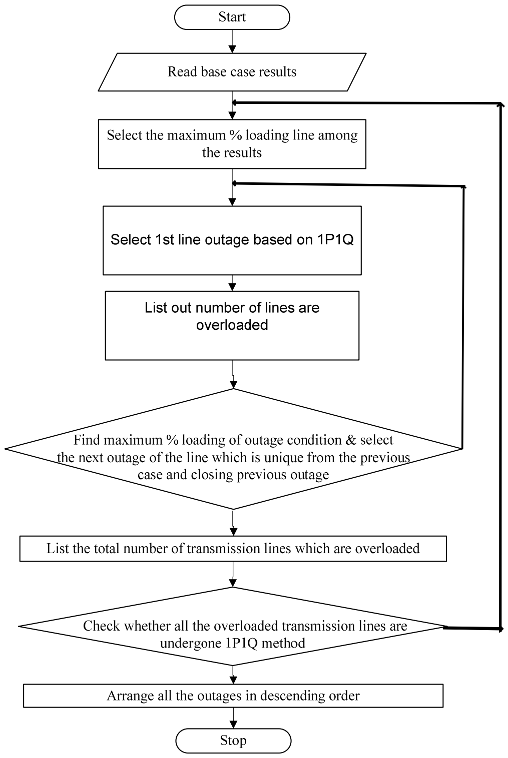

Fig. 1. Flowchart for outages according to their priority

3. Load modelling. Contingency occur mainly due sudden increase or decrease of loads. Load modelling plays a major role in analyzing various types of loads. Load modelling refers to the mathematical illustration of the connection between the power and the voltage in a load bus. It has a significant impact on power system studies [12-14]. Two types of load models are considered in this project for analyzing the contingency – steady state load model and polynomial load model.

3.1 Steady state load model. Steady state load model is also known as constant load model [15]. The active and reactive power equations in this model are represented as

$$P_i = \sum_{j=1}^{n} V_i Y_{ij} V_j \cos\left(\theta_{ij} + \delta_j - \delta_i\right); \qquad (1)$$

$$Q_i = -\sum_{j=1}^{n} V_i Y_{ij} V_j \sin\left(\theta_{ij} + \delta_j - \delta_i\right), \qquad (2)$$

where P_i and Q_i be the active and reactive power diagonal and off-diagonal elements of active power and reactive power are developed.

3.2 Polynomial load model. Polynomial load model is also known as ZIP load model. *Z* represents constant impedance, *I* represent constant current and *P* represents constant power. The active and reactive power equations in this model are represented in (3), (4). At bus-*i*:

$$P_i = \left[\sum_{j=1}^{n} V_i Y_{ij} V_j \cos\left(\delta_{ij} + \theta_j - \theta_i\right)\right]\left[P_1 V_i^2 + P_2 V_i + P_3\right]. \qquad (3)$$

$$Q_i = \left[-\sum_{j=1}^{n} V_i Y_{ij} V_j \sin\left(\delta_{ij} + \theta_j - \theta_i\right)\right]\left[P_1 V_i^2 + P_2 V_i + P_3\right]. \qquad (4)$$

At bus-*j*:

$$P_j = \left[\sum_{i=1}^{n} V_j Y_{ji} V_i \cos\left(\delta_{ji} + \theta_i - \theta_j\right)\right]\left[P_1 V_j^2 + P_2 V_j + P_3\right]; \qquad (5)$$

$$Q_j = \left[-\sum_{i=1}^{n} V_j Y_{ji} V_i \sin\left(\delta_{ji} + \theta_i - \theta_j\right) \right] \left[P_1 V_j^2 + P_2 V_j + P_3 \right], \quad (6)$$

where P_i, P_j and Q_i, Q_j are the active and reactive power values at buses i and j; V_i, V_j are the nodal voltage values at buses i and j respectively; δ_{ij} is the angle voltage of unit i and j; Y_{ji} is the admittances of the line; P_1, P_2 and P_3 represents the ZIP load parameters.

The diagonal and off-diagonal elements of active power and reactive power at bus-i and bus-j are developed. These load models are incorporated with Newton-Raphson power flow solution method. Newton-Raphson method is used as it is faster, more reliable; results are accurate and quadratic type convergence. Jacobian matrix is formed using the developed diagonal and off-diagonal elements. The Jacobian matrix springs the linear connection between the small vagaries in voltage magnitude and phase angle with the small vagaries in real and reactive power as:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix}, \quad (7)$$

where J_1, J_2, J_3 and J_4 are the Jacobean matrix of Newton-Rapson method. The variance between the programmed and the designed values known as power residual is given in (8), (9)

$$\Delta P_i^k = P_i^{sch} - P_i^k; \quad (8)$$

$$\Delta Q_i^k = Q_i^{sch} - Q_i^k. \quad (9)$$

The new estimates for voltage angle and voltage magnitude are shown in (10), (11):

$$\delta_i^{k+1} = \delta_i^k - \Delta\delta_i^k; \quad (10)$$

$$\left|V_i^{k+1}\right| = \left|V_i^k\right| - \left|\Delta V_i^k\right|. \quad (11)$$

These two load models are applied to IEEE 118 bus system for analyzing the behavior of the loads. Line stability index gives support to find most severe lines.

4. Hybrid line stability ranking index (HLSRI) for contingency ranking. To derive the HLSRI we first consider the line stability index (LSI or L_{mn}) and the fast voltage stability index (FVSI). We then showed that the FVSI is a calculation of the L_{mn} and proceed to derive the HLSRI for better precision and speed. L_{mn} index is given in (12) [16]:

$$L_{mn} = \frac{4XQ_n}{\left[V_m \sin(\theta - \delta)\right]^2} \le 1, \quad (12)$$

where $\delta = \delta_m - \delta_n$; V_m is the voltage magnitude; X is the reactance of the transmission line.

The FVSI is derived from L_{mn} when the voltage angle difference between sending and receiving end is assumed to be very small (i.e., $\delta = 0$). Then FVSI is show in (13):

$$FVSI = \frac{4Q_n \cdot \left(\left|Z^2\right|\right)}{\left[\left|V_m\right|^2 \cdot X\right]} \le 1, \quad (13)$$

where Q_n is the reactive power at receiving end; Z is the impedance of the line; X is the reactance of the line.

We therefore propose to combine (13) and (14) into a single equation to compute a HLSRI rendering to a switching function β, as shown in (14). Each value of δ computed from the load-flow program is tested against a threshold value δ_C to determine whether β is 1 or 0. The proposed index is formed by combining (12) and (13) into one to produce a HLSRI show in (14) that gain more accuracy and fastness with improved line stability. The HLSRI is given as formulation of FVSI:

$$HLSRI = \frac{4XQ_n}{\left[V_m\right]^2} \left[\frac{|Z|^2}{X_{Line}} \beta - \frac{XQ_n}{\left[\sin(\theta - \delta)\right]^2} (\beta - 1) \right] \le 1, \quad (14)$$

where $\beta = \begin{cases} 1 & \delta < \delta_C \\ 0 & \delta \ge \delta_C \end{cases},$

where δ is used as modifier; β is used as switching function.

When HLSRI is less than 1, the system is stable or HLSRI is approached to one, then the system is unstable.

Table 1 shows the proposed index value in ZIP load model without contingency of IEEE 14 test system. It has 5 generator buses (PV), 9 load buses (PQ) and 20 interconnected lines or branches. Various indices value with proposed index as shown in the Table 1.

Table 1

Comparison between indices values of proposed index with LSI and FVSI

S. no	From	To	Index		
			LSI	FVSI	HLSRI
1	1	2	0.0286	0.0287	0.0287
2	2	3	0.0259	0.0259	0.0259
3	2	4	0.0004	0.0004	0.0004
4	1	5	0.008	0.008	0.008
5	2	5	0.0026	0.0026	0.0026
6	3	4	0.011	0.011	0.011
7	4	5	0.0067	0.0067	0.0067
8	5	6	0.0159	0.0159	0.0159
9	4	7	0.0618	0.0616	0.0618
10	7	8	0.0425	0.0425	0.0425
11	4	9	0.0406	0.0406	0.0406
12	7	9	0.0022	0.0022	0.0022
13	9	10	0.0083	0.0083	0.0083
14	6	11	0.037	0.037	0.037
15	6	12	0.0662	0.0663	0.0663
16	6	13	0.0114	0.0114	0.0114
17	9	14	0.0456	0.0455	0.0455
18	10	11	0.2916	0.264	0.264
19	12	13	0.0097	0.0098	0.0098
20	13	14	0.0507	0.0509	0.0509

From the Table 1 it is evidence that, instead of using two individual line indexes, the proposed HLSRI values are very close to the other indices and more accuracy.

5. Power system contingency ranking algorithm is shown below.

Stage 1. Recite the given system line data and the bus data.

Stage 2. Without seeing the line contingency perform the load flow analysis for the base case.

Stage 3. Simulate a line outage or line contingency i.e. removing a line proceeding to the next step.

Stage 4. Load flow analysis is done for this specific outage then calculation of the active power flow is done in the lasting lines and value of $P_{\max}$ is also calculated.

Stage 5. Subsequently for the exact line contingency, voltages of all the load buses are designed.

Stage 6. Then HLSRI is being calculated which indicates the voltage collapse.

Stage 7. Stages 3 to 6 for all the line voltages is repeated to obtain HLSRI.

Stage 8. Contingencies are ranked based on the sternness of the contingency.

The proposed HLSRI is investigated with IEEE 14 bus system with contingency (single line outage) as shown in Fig. 2.

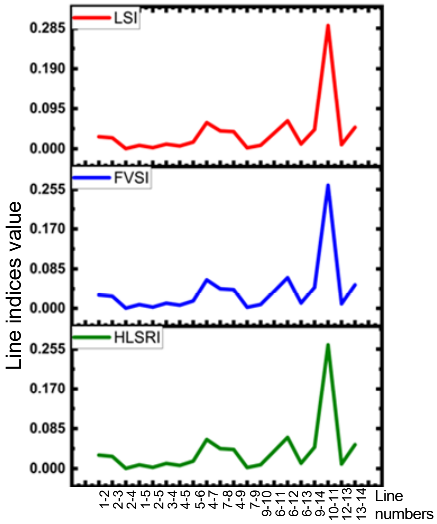

Fig. 2. Proposed index value with LSI and FVSI using contingency

From Fig. 2 the proposed index gives more accuracy and fastness in the stability value in the contingency when compared to others. First five ranks considered as most critical lines, and rank 6 to 16 considered as semi critical and ranks 17 to 20 considered as non-critical line, so in this paper most critical lines are analyzed with compensation to maintain the system stable and secure. Table 2 illustrates the data of tuned UPFC devices placed at critical location for compensation in contingency. Figure 2 shows the comparison between proposed index with others when line no. 4-7 gets outage then severity of the lines along with ranking shown in Table 2.

Table 2

Tuned UPFC devices placed at critical location for compensation in contingency

Rank	From	To	V_m, p.u	P, MW	Q, MVAr	P_{losses}, MW	Q_{losses}, MVAr
1	10	11	1.026	14.62	11.14	2.37	–27.22
2	6	12	1.12	26.16	24.57	5.53	–19.47
3	13	14	1.083	16.43	19.4	2.14	–24.12
4	9	14	1.034	14.22	12.52	2.00	–24.12
5	6	11	1.12	23.29	–6.67	6.59	–20.86

The above analysis is also carried out for IEEE 118 test system with different percentage of loadings in contingency analysis.

6. Unified power flow controller. A FACTS device plays a vital role in controlling power and enhancing the working volume of existing lines. Basic purpose of the parallel inverter is to supply real power required by the series inverter through the common DC link. The parallel inverter can also grip or produce controllable reactive power as shown in Fig. 3 [17, 18].

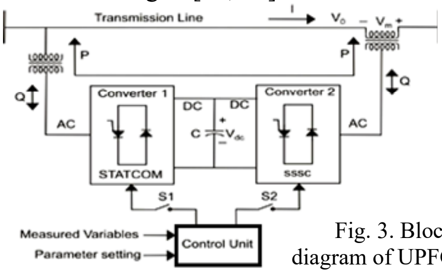

Fig. 3. Block diagram of UPFC

The active and reactive power equation of the UPFC [19] is developed with ZIP load model as shown in:

$$P_i = \left\{ \begin{aligned} &\left[\frac{-2R_{se} r V_i^2 \cos\gamma}{R_{se}+X_{se}}\right] + \left[\frac{r V_i^2 X_{se}\sin\gamma}{R_{se}^2+X_{se}^2}\right] - \left[\frac{R_{se} r^2 V_i^2}{R_{se}^2+X_{se}^2}\right] - \\ &-\left[\frac{r V_i V_j X_{se}\sin(\theta_i+\gamma-\theta_j)}{R_{se}^2+X_{se}^2}\right] + \left[\frac{r V_i V_j R_{se}\cos(\theta_i+\gamma-\theta_j)}{R_{se}^2+X_{se}^2}\right] \end{aligned} \right\} \times \tag{15}$$
$$\times \left\{P_1 V_i^2 + P_2 V_i + P_3\right\};$$

$$Q_i = \left[\frac{-r V_i V_j}{R_{se}^2+X_{se}^2}\right]\cdot\left\{X_{se}\cos\gamma - R_{se}\sin\gamma\right\}\cdot\left\{P_1 V_i^2 + P_2 V_i + P_3\right\}; \tag{16}$$

$$P_j = \left[\frac{r V_i V_j}{R_{se}^2+X_{se}^2}\right]\cdot\left\{R_{se}\cos(\theta_i+\gamma-\theta_j) + X_{se}\sin(\theta_i+\gamma-\theta_j)\right\}\times \tag{17}$$
$$\times\left\{P_1 V_i^2 + P_2 V_i + P_3\right\};$$

$$Q_j = \left[\frac{r V_i V_j}{R_{se}^2+X_{se}^2}\right]\cdot\left\{X_{se}\cos(\theta_i+\gamma-\theta_j) - R_{se}\sin(\theta_i+\gamma-\theta_j)\right\}\times \tag{18}$$
$$\times\left\{P_1 V_i^2 + P_2 V_i + P_3\right\},$$

where P_i, P_j, Q_i, Q_j are the active and reactive power at i^{th} and j^{th} bus; R_{se} and X_{se} are the resistance and reactance of the line.

The crosswise and off-diagonal elements are developed. By using this developed mathematical model, MATLAB program is developed and used for compensating the most severe lines.

7. Results and discussion. In this paper, the IEEE 14 test bus system shown for 100 % loading along with compensation as shown in Table 2.

From the below Table 3, it shows the power flows without UPFC compensation for 100 % loading (which find with the help of proposed index).

Table 3

Results of ZIP load modeling for 100 % loading

Rank	From	To	P, MW	Q, MVAr	V_m, p.u	P_{losses}, MW	Q_{losses}, MVAr
ZIP load modeling							
1	70	74	17.1	14.03	0.99	107.8	1758
2	71	72	15.1	–10.14	0.996	137.8	1758
3	24	72	–3.02	–4.11	1	137.8	1758
4	24	70	–11.0	–7.45	1	137.8	1758
5	92	100	32.0	–13.30	0.99	137.8	1758
Z load modeling alone							
1	70	74	18.6	21.06	0.99	144.9	–1729
2	71	72	20.0	–11.19	1.001	144.9	–1729
3	24	72	–7.7	–2.87	1	144.9	–1729
4	24	70	–16.0	–7.14	1	144.9	–1729
5	92	100	32.0	–13.3	0.99	144.9	–1729
I load modeling alone							
1	70	74	17.21	14.03	0.99	137.6	1760
2	71	72	15.06	–10.1	0.996	137.6	1760
3	24	72	–2.94	–4.13	1	137.6	1760
4	24	70	–10.92	–7.46	1	137.6	1760
5	92	100	31.30	–13.2	0.99	137.6	1760
P load modeling							
1	70	74	16.77	14.15	0.99	133.0	–1775
2	71	72	9.92	–8.96	0.996	133.0	–1775
3	24	72	2.13	–5.40	1	133.0	–1775
4	24	70	–5.55	–7.67	1	133.0	–1775
5	92	100	30.86	–13.1	0.99	133.0	–1775

IEEE 118 bus test system which consists of 1 slack bus, 69 load buses, 48 generator buses and 179 transmission lines is simulated using MATLAB for ZIP load modeling and individual *Z*, *I*, *P* load modeling and following results are obtained for different loading conditions without contingency. Tables 4 and 5 shows the ZIP and individual *Z*, *I*, *P* load model with 100 % and 150 % of loading for the critical lines without contingency.

At a time, single line outage is performed, and the stability is analysed on IEEE 118 bus system by observing the standards of voltage profile, active and reactive power flows and total power loss. All the lines are graded affording to the values of a HLSRI. Among 179 ranks, 1 to 8 ranks are identified as most critical lines and the below tables shows the results for these 8 most critical lines obtained while performing contingency and shows the results obtained after compensating the most critical lines.

Table 4

Results of ZIP, *Z*, *I*, *P* load modeling for 100 % loading with contingency

Rank	From	To	HLSRI	V_m, p.u	*P*, MW	*Q*, MVAr	P_{losses}, MW	Q_{losses}, MVAr
ZIP load modelling								
1	70	74	1.086	0.99	25	8	139.60	–1732
2	71	72	0.965	0.99	15	20	140.54	–1734
3	24	72	0.847	1.01	7	3	140.08	–1737
4	24	70	0.759	1.01	7	3	151.89	–1675
5	92	100	0.542	1	10	8	140.34	–1732
Z load modelling alone								
1	70	74	1.065	1	138.09	17	145.14	–1723
2	71	72	0.999	0.99	66	20	144.53	–1719
3	24	72	0.843	1.01	7	3	144.21	–1723
4	24	70	0.758	1.01	7	3	158.43	–1652
5	92	100	0.537	1	10	8	145.05	–1718
I load modelling alone								
1	70	74	1.086	1	25	8	138.09	–1752
2	71	72	0.96	0.99	66	20	137.47	–1750
3	24	72	0.848	1.01	7	3	137.34	–1754
4	24	70	0.76	1.01	7	3	148.85	–1692
5	92	100	0.532	1	10	6	137.84	–1747
P load modelling alone								
1	70	74	1.102	1	25	8	138.09	–1752
2	71	72	0.93	0.99	66	20	137.47	–1750
3	24	72	0.858	1.01	7	3	137.34	–1754
4	24	70	0.766	1.01	7	3	148.85	–1692
5	92	100	0.522	1	10	10	137.84	–1747

Table 5

Results of ZIP, *Z*, *I*, *P* load modeling for 150 % loading

Rank	From	To	*P*, MW	*Q*, MVAr	V_m, p.u	P_{losses}, MW	Q_{losses}, MVAr
	ZIP load modeling						
1	70	74	5.179	–4.58	0.95	861.6	616.43
2	71	72	163.36	–33.4	0.969	861.6	616.43
3	24	72	–123.6	44.32	1	861.6	616.43
4	24	70	–142.77	52.42	1	861.6	616.43
5	92	100	–223.27	433.0	0.98	861.6	616.43
	Z load modeling alone						
1	70	74	–350.31	254.3	0.95	544.3	307.91
2	71	72	9131.19	1890	6.72	544.3	307.91
3	24	72	–308.57	724.0	1	544.3	307.91
4	24	70	12.218	2.207	1	544.3	307.91
5	92	100	–223.2	433.0	0.98	544.3	307.91
	I load modeling alone						
1	70	74	5.246	–4.606	0.95	862.8	2622.87
2	71	72	163.3	–33.492	0.969	862.8	2622.87
3	24	72	–123.6	44.35	1	862.8	2622.87
4	24	70	–142	52.45	1	862.8	2622.87
5	92	100	22.46	–11.906	0.98	862.8	2622.87
	P load modeling alone						
1	70	74	7.975	–5.4015	0.95	695.3	1615.45
2	71	72	138.394	–34.067	0.971	695.3	1615.45
3	24	72	–104.80	34.238	1	695.3	1615.45
4	24	70	–123.65	38.692	1	695.3	1615.45
5	92	100	22.305	–8.7145	0.99	695.3	1615.45

Table 6 and 7 shows the values for HLSRI of ZIP load model with 100 % and 150 % loading with contingency. Table 8 shows the ZIP load model with compensation for the critical lines which is ranked from 1 to 8 with different percentage of loading.

In Table 6, $|r|$ denotes ratio of sending end voltage and injected voltage; γ is the angle between the voltages.

Table 6

Results of ZIP, *Z*, *I*, *P* load modeling for 100 % loading with UPFC compensation

Rank	From	To	*r*	γ	V_m, p.u	*P*, MW	*Q*, MVAr	P_{losses}, MW	Q_{losses}, MVAr
ZIP load modelling									
1	70	74	0.1	10	0.96	41.8	88.3	130	–1777
2	71	72	0.1	15	0.96	21.5	36.2	132	–1778
3	24	72	0.1	10	0.96	14.2	45.8	132	–1777
4	24	70	0.3	20	0.96	16.6	75.9	131	–1767
5	92	100	0.1	1	0.96	40.5	19.9	133	–1774
Z load modelling									
1	70	74	0.1	5	0.96	40.5	81.49	132	–1778
2	71	72	0.1	10	0.96	21.0	37.47	132	–1779
3	24	72	0.1	6	0.96	14.4	46.31	132	–1779
4	24	70	0.8	120	0.96	156.	36.28	125	–1677
5	92	100	0.7	5	0.96	33.8	–5.57	133	–1775
I load modelling									
1	70	74	0.1	5	0.96	40.4	81.51	132	–1778
2	71	72	0.1	5	0.96	19.0	38.27	132	–1778
3	24	72	0.1	2	0.96	12.6	47.03	132	–1778
4	24	70	0.8	120	0.96	15.6	36.28	125	–1677
5	92	100	0.5	5	0.96	32.0	–10.1	133	–1775
P load modelling									
1	70	74	0.1	5	0.96	32.4	82.12	135	–1766
2	71	72	0.1	10	0.96	17.3	37.34	133	–1772
3	24	72	0.1	5	0.96	8.11	48.01	134	–1771
4	24	70	0.8	120	0.96	15.6	36.44	125	–1677
5	92	100	0.5	5	0.96	35.9	2.52	132	–1776

From the results it is clear that the values of the transmission line parameters are improved after compensation compared to before compensation. For example, between buses 70 and 74 when performing load modelling, results are active power 17.184 MW, reactive power 14.0386 MVAr, voltage profile 0.99, total system loss 107.815 MW and when contingency is created the results are active power 25 MW, reactive power 8 MVAr, voltage profile 0.99, total system loss 139.60 MW and finally after providing compensation results are active power 41.878 MW, reactive power 88.37 MVAr, voltage profile 0.96, total system loss 130.43 MW. This shows that after providing compensation voltage profile is maintained, active power flow is increased, reactive power flow is maintained, and the total system losses are condensed and hence the system is maintained stable.

Table 7

Results of ZIP, *Z*, *I*, *P* load modeling for 150 % loading with contingency

Rank	From	To	HLSRI	V_m, p.u	*P*, MW	*Q*, MVAr	P_{losses}, MW	Q_{losses}, MVAr
ZIP load modelling								
1	69	75	7.78	0.97	54	200	896	2833
2	69	77	3.95	0.97	54	200	904	2846
3	70	74	2.00	1	66	120	1649	6692
4	24	70	1.82	0.99	10.5	4.5	1550	6188
5	76	77	1.20	0.91	70.5	16.5	915	2925
I load modelling alone								
1	69	75	6.81	0.97	54	200	864	2641
2	69	77	3.70	0.97	54	200	872	2653
3	70	74	1.88	1	66	120	644	1654
4	24	70	1.35	0.99	10.5	4.5	1649	6692
5	75	77	1.16	0.95	102	40.5	950	3712
P load modelling alone								
1	69	75	4.22	0.97	54	200	695	1626
2	69	77	2.33	0.97	54	200	702	1636
3	70	74	1.20	1	66	120	644	1654
4	24	70	0.96	0.99	10.5	4.5	914	2729
5	75	77	0.93	0.95	102	40.5	745	2358

Table 8
Results of ZIP, *Z*, *I*, *P* load modeling for 150 % loading with UPFC compensation

Rank	From	To	*r*	Gamma	V_m, p.u	*P*, MW	*Q*, MVAr	P_{losses}, MW	Q_{losses}, MVAr
ZIP load modelling									
1	69	75	0.1	10	0.95	437	83.6	689	1565
2	69	77	0.1	10	0.95	587	125	692	1562
3	70	74	0.2	5	0.95	30.5	59.6	692	1599
4	24	70	0.1	15	0.95	–128	63.2	692	1593
5	76	77	0.5	15	0.95	67	417	735	1726
I load modelling									
1	69	75	0.1	1	0.95	430	84	688	1564
2	69	77	0.1	4	0.95	581	124	690	1559
3	70	74	0.6	75	0.95	322	194	651	1356
4	24	70	0.4	68	0.95	–63.5	68	661	1385
5	75	77	0.5	77	0.95	234	63	676	1453
P load modelling									
1	69	75	0.4	20	0.95	620	303	700	1504
2	69	77	0.3	65	0.95	768	214	722	1558
3	70	74	0.2	20	0.95	59	132	689	1584
4	24	70	0.1	10	0.95	–128	63	692	1592
5	75	77	0.5	33	0.95	158	171	708	1610

8. Conclusions. The proposed index is applied for IEEE 14, 118 test system and mathematical model of steady state and polynomial load models (ZIP) are developed and analyzed with the IEEE test system by in view of the single line outage at a time. IEEE 118 test system is analyzed for various percentages of ZIP load model for contingency with and without compensation. A hybrid line stability ranking index shows the most critical lines in the system for which compensation is provided by placing unified power flow controller with proper tuned. Based on the outcomes it is apparent that the stress level is reduced, and the system is maintained stable and healthy by providing suitable compensation at suitable location.

Conflict of interest. The authors declare that they have no conflicts of interest

REFERENCES

1. Mishra A., Kumar G.V.N. A risk of severity based scheme for optimal placement of interline power flow controller using composite index. *International Journal of Power and Energy Conversion*, 2017, vol. 8, no. 3, pp. 257-275. doi: https://doi.org/10.1504/IJPEC.2017.10003636.
2. Venkatesh P., Visali N. Assessment of Power System Security Using Contingency Analysis. *International Journal of Control and Automation*, 2019, vol. 12, no. 5, pp. 25-32. doi: https://doi.org/10.33832/ijca.2019.12.5.03.
3. Venkateswaran J., Manohar P., Vinothini K., Shree B.T.M., Jayabarathi R. Contingency analysis of an IEEE 30 bus system. *2018 3rd IEEE International Conference on Recent Trends in Electronics, Information & Communication Technology (RTEICT)*, 2018, pp. 328-333. doi: https://doi.org/10.1109/RTEICT42901.2018.9012509.
4. Angadi R.V., Daram S.B., Venkataramu P.S. Contingency Analysis of Power System using Big Data Analytic Techniques. *2020 5th International Conference on Computing, Communication and Security (ICCCS)*, 2020, pp. 1-7. doi: https://doi.org/10.1109/ICCCS49678.2020.9276796.
5. Arif A., Wang Z., Wang J., Mather B., Bashualdo H., Zhao D. Load Modeling – A Review. *IEEE Transactions on Smart Grid*, 2018, vol. 9, no. 6, pp. 5986-5999. doi: https://doi.org/10.1109/TSG.2017.2700436.
6. Seshapalli S.R. Analysis of Hybrid Power Flow Controller using Static load model under Contingency Screening. *2019 IEEE International Conference on Clean Energy and Energy Efficient Electronics Circuit for Sustainable Development (INCCES)*, 2019, pp. 1-6. doi: https://doi.org/10.1109/INCCES47820.2019.9167709.
7. Asawa S., Al-Attiyah S. Impact of FACTS device in electrical power system. *2016 International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT)*, 2016, pp. 2488-2495. doi: https://doi.org/10.1109/ICEEOT.2016.7755141.
8. Chorghade A., Kulkarni Deodhar V.A. FACTS Devices for Reactive Power Compensation and Power Flow Control – Recent Trends. *2020 International Conference on Industry 4.0 Technology (I4Tech)*, 2020, pp. 217-221. doi: https://doi.org/10.1109/I4Tech48345.2020.9102640.
9. Suresh K., Parimalasundar E. A Modified Multi Level Inverter with Inverted SPWM Control. *IEEE Canadian Journal of Electrical and Computer Engineering*, 2022, vol. 45, no. 2, pp. 99-104. doi: https://doi.org/10.1109/ICJECE.2022.3150367.
10. Sairam S., Daram S.B. Contingency Ranking in a Power Transmission System using ZIP Load Modeling. *UPB Scientific Bulletin, Series C: Electrical Engineering and Computer Science*, 2020, vol. 82, no. 1, pp. 205-220.
11. Ding T., Li C., Yan C., Li F., Bie Z. A Bilevel Optimization Model for Risk Assessment and Contingency Ranking in Transmission System Reliability Evaluation. *IEEE Transactions on Power Systems*, 2017, vol. 32, no. 5, pp. 3803-3813. doi: https://doi.org/10.1109/TPWRS.2016.2637060.
12. Suresh K., Parimalasundar E. Design and Implementation of Universal Converter. *IEEE Canadian Journal of Electrical and Computer Engineering*, 2022, vol. 45, no. 3, pp. 272-278. doi: https://doi.org/10.1109/ICJECE.2022.3166240.
13. Ram S.S., Daram S.B., Venkataramu P.S., Nagaraj M.S. Analysis of ZIP Load Modeling in Power Transmission System. *International Journal of Control and Automation*, 2018, vol. 11, no. 7, pp. 11-24. doi: https://doi.org/10.14257/ijca.2018.11.7.02.
14. Suresh K., Parimalasundar E. A novel dual-leg DC-DC converter for wide range DC-AC conversion. *Automatika*, 2022, vol. 63, no. 3, pp. 572-579. doi: https://doi.org/10.1080/00051144.2022.2056809.
15. Chappa H., Thakur T. A novel load shedding methodology to mitigate voltage instability in power system. *Electrical Engineering & Electromechanics*, 2022, no. 3, pp. 63-70. doi: https://doi.org/10.20998/2074-272X.2022.3.09.
16. Ezhilvannan P., Krishnan S. An Efficient Asymmetric Direct Current (DC) Source Configured Switched Capacitor Multi-level Inverter. *Journal Européen Des Systèmes Automatisés*, 2020, vol. 53, no. 6, pp. 853-859. doi: https://doi.org/10.18280/jesa.530611.
17. Yari S., Khoshkhoo H. Assessment of line stability indices in detection of voltage stability status. *2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, 2017, pp. 1-5. doi: https://doi.org/10.1109/EEEIC.2017.7977454.
18. Goutham N.S., Dr. Mohd. Z. A. Ansari. Determination of Optimal Location of FACTS Devices for Power System Restoration Including Load Flow and Contingency Analysis, *International Journal of Engineering Research & Technology (IJERT)*, 2017, vol. 5, no. 18, pp. 1-4. doi: https://doi.org/10.17577/IJERTCONV5IS18004.
19. Praveen Kumar T., Ganapathy S., Manikandan, M. Improvement of voltage stability for grid connected solar photovoltaic systems using static synchronous compensator with recurrent neural network. *Electrical Engineering & Electromechanics*, 2022, no. 2, pp. 69-77. doi: https://doi.org/10.20998/2074-272X.2022.2.10.

Received 25.06.2022
Accepted 12.09.2022
Published 06.01.2023

Peruthambi Venkatesh[1], *Research Scholar*,
Nagalamadaka Visali[1], *Professor*,
[1] Department of Electrical & Electronics Engineering,
JNTUA College of Engineering (Autonomous) Ananthapuramu,
Ananthapuramu-515002, Andhra Pradesh, India,
e-mail: venkateshp.engg@gmail.com (Corresponding Author);
nvisali.eee@jntua.ac.in

How to cite this article:
Venkatesh P., Visali N. Investigations on hybrid line stability ranking index with polynomial load modeling for power system security. *Electrical Engineering & Electromechanics*, 2023, no. 1, pp. 71-76. doi: https://doi.org/10.20998/2074-272X.2023.1.10