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# A MODIFIED LINE STABILITY INDEX BASED ON THE SHORT PATH METHOD (MLSISP) FOR VOLTAGE COLLAPSE PREDICTION

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**Abstract-** The problem of voltage stability presents a permanent constraint to power system management and planning. This leads power managers and operators to seek to improve their techniques for predicting and controlling the voltage collapse phenomenon. Hence the usefulness of the present paper, which consists in developing a modified line stability index using the short path to the nearest generator method (MLSI$_{SP}$), is capable of identifying fragile buses and lines for different disturbances and test networks. An in-depth comparative study has been carried out to assess the sensitivity and reliability of the proposed index compared with indices widely used in the literature. The study included various scenarios, such as increases in active load, reactive load, and line outages. The results of this comparison demonstrated that the proposed index accurately predicts voltage stability, classifies lines according to their criticality, and provides reliable estimates of reactive and active stability margins in baseline and high disturbance scenarios. The simulation has been performed by MATLAB R2023a software, using IEEE 14-bus and IEEE 30-bus test networks.

**Keywords:** Contingency Analysis, *FVSI*, Index, Line Index, $L_{mn}$, *LPP*, *LQP*, MLSI$_{SP}$, *NLSI*, Sensitivity Analysis, Short Path Method, Voltage Collapse, Voltage Stability Indices.

## 1. INTRODUCTION

The global energy demand has been steadily increasing in various regions across the world. Electricity systems must therefore maintain a strict balance between energy production and consumption. Indeed, the electricity network managers are supposed to ensure that the needs of the consumers are met. At each moment, they have to verify the equality: Production = Consumption + Losses. This equation called the electrical network control equation, is subject to several constraints. Namely, the high consumption of electrical energy, the governmental policies of austerity, and the ecological pressure of the population make electrical networks more complex to be planned, managed, and protected. As a result, networks are found in a situation close to the capacity limits, and eventually, many blackouts occur [1, 2].

One of the major causes of blackouts is due to the problem of voltage collapse [3]. Therefore, operators pay special attention to the prediction and control of voltage collapse to maintain the stability of networks and avoid major blackouts. For this purpose, various voltage stability indices for voltage collapse prediction have been proposed in the literature [4-7]. Such voltage stability indices are computed for a bus, a line, or the entire network (global indices) [8]. Among the above-mentioned indices, the global indices are better than the line and bus indices in terms of accuracy. However, their complexity is higher and their computation time is always a problematic element. On the other hand, line indices capable of identifying critical lines can provide a more accurate assessment with lower computational time compared to bus and global indices [8]. Therefore, line voltage stability indices seem to be effective tools for voltage stability assessment [10].

In this article, a modified line voltage stability index based on the short method named (MLSI$_{SP}$) is suggested. In addition to taking into consideration the two-line parameters $X$ and $R$ as well as the two reactive and active powers, it is also sensitive to the voltage angle difference between the transmitter and receiver bus ($\delta$). The new index can predict voltage stability with more accuracy. It can be used to identify sensitive areas and to follow closely the evolution of reactive and active power. The present paper is structured as follows: An outline for some line indices already reported in the literature is presented in section 2. The development of the new index is the subject of section 3. Section 4 presents the test networks and the methodology used for the evaluation of the MLSI$_{SP}$ index. Section 5 is devoted to the comparison of the proposed index with other line indices. Moreover, sensitivity studies of different load disturbances and variations of reactive and active power as well as contingency analyses have been discussed in this section. Finally, Section 6 features the conclusion.

## 2. A BRIEF OVERVIEW OF SOME VOLTAGE STABILITY LINE INDICES

The indices presented in this section are based on the model formed by the reference two-bus link appearing in Figure 1.

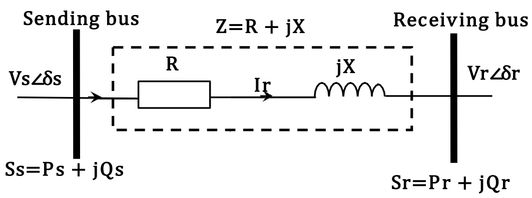


Figure 1. Two-bus model

### 2.1. Fast Voltage Stability Index (*FVSI*)

Musirin derives an index using the concept of single-line energy transmission. This index can be implemented to identify the system's weakest line from voltage and reactive power measurements. It is presented in the following form [11]:

$$FVSI = \frac{4Z^2 Q_R}{V_S{}^2 X} \tag{1}$$

The *FVSI* formulation ignores the shunt admittance ($Y$) as well as the voltage angle ($\delta$). The *FVSI* index values of all lines must not exceed 1 to ensure voltage stability.

### 2.2. Line Stability Index $L_{mn}$

The $L_{mn}$ suggested by Moghavvemmi is founded on the identical concept to *FVSI*. The index $L_{mn}$ is reformulated without considering the shunt admittance and real power, as follows [12]:

$$L_{mn} = 4\frac{Q_r X}{(V_s \sin(\theta - \delta))^2} \tag{2}$$

The network achieves its limit of stability when the value of a line's $L_{mn}$ index approaches unity.

### 2.3. Line Stability Factors (LQP and LPP)

Mohamed, et al., established two indices of voltage stability which are:

The reactive power change sensitive index *LQP* is derived by considering the reactive power balance. *LQP* is established as follows [13]:

$$LQP = 4\frac{X}{V_s^2}(Q_r + P_s^2 s^2 \frac{X}{V_s^2}) \tag{3}$$

The *LPP* index is based on the identical reasoning of the *LQP* index. This index is affected by active power variation as it is obtained using the active power balance [13].

$$LPP = \frac{4R}{V_s^2}(P_r + Q_s^2 \frac{R}{V_s^2}) \tag{4}$$

To keep the system's voltage stability, the value of these two indices must be smaller than 1.

### 2.4. Novel Line Stability Index (*NLSI*)

Using the identical concept of energy transmission employed in the above-mentioned indices, Yazdanpanah-Goharrizi, et al. developed the *NLSI* index. This index is calculated by the Equation (5) [14]:

$$NLSI = 4\frac{P_r R + Q_r X}{V_s^2} \tag{5}$$

The researchers have ignored the shunt admittance and the angle difference between the voltage line's ends. Like all the last indices, this index must remain below 1 to guarantee the electrical system's voltage stability.

## 3. PROPOSED INDEX: MODIFIED LINE STABILITY INDEX BASED SHORT PATH METHOD ($MLSI_{SP}$)

Based on the line model as shown in Figure 1, the complex apparent power of the bus $r$ can be written in receiver convention as follows [6]:

$$\underline{S_r} = \underline{V_r I_r^*} \tag{6}$$

$$\underline{I_r} = (\frac{\underline{S_r}}{\underline{V_r}})^* = \frac{(P_r - jQ_r)}{V_r \angle -\delta_r} \tag{7}$$

The current through the line is also presented by the Equation (8) [6]:

$$\underline{I_r} = \frac{V_s \angle \delta_s - V_r \angle \delta_r}{R + jX} \tag{8}$$

From Equations (7) and (8) [6]:

$$\frac{V_s \angle \delta_s - V_r \angle \delta_r}{R + jX} = \frac{(P_r - jQ_r)}{V_r \angle -\delta_r} \tag{9}$$

Then [6]:

$$V_s V_r \angle(\delta_s - \delta_r) - V_r{}^2 = P_r R + Q_r X - jQ_r R + jP_r X \tag{10}$$

Setting [6]: $\delta_s - \delta_r = \delta$

Equation (10) becomes as follows [6]:

$$V_s V_r \angle\delta - V_r{}^2 = P_r R + Q_r X - jQ_r R + jP_r X \tag{11}$$

Using the rectangular shape $V_s V_R \angle\delta$, Equation (12) is obtained [6]:

$$V_s V_r \cos\delta + jV_s V_r \sin\delta - V_r{}^2 = P_r R + Q_r X - jQ_r R + jP_r X \tag{12}$$

The following two equations are obtained when the imaginary and real parts of (12) are separated [6]:

$$V_s V_r \cos\delta - V_r{}^2 = P_r R + Q_r X \tag{13}$$

$$V_s V_r \sin\delta = P_r X - Q_r R \tag{14}$$

From Equation (13), the Equation (15) for $P_r$ is found [6]:

$$P_r = \frac{-Q_r X + V_s V_r \cos\delta - V_r{}^2}{R} \tag{15}$$

$$V_r{}^2 - V_s V_r \cos\delta + RP_r + XQ_r = 0 \tag{16}$$

The real, non-zero values of $V_r$ are obtained by fixing the discriminant of equation (16) over zero:

$$\Delta = (-V_s \cos\delta)^2 - 4(RP_r + XQ_r) \geq 0 \tag{17}$$

$$MLSI = \frac{4(RP_r + XQ_r)}{(V_s \cos\delta)^2} \tag{18}$$

Using the short path method shown in Figure 2. The shortest path (path with the lowest impedance) between the receiving and the sending bus corresponding to the nearest generator [10] is determined. Then, the *MLSI* index proposed above becomes as follows:

$$MLSI_{SP} = \frac{4(RP_L + XQ_L)}{(V_{th} \cos\delta)^2} \leq 1 \tag{19}$$

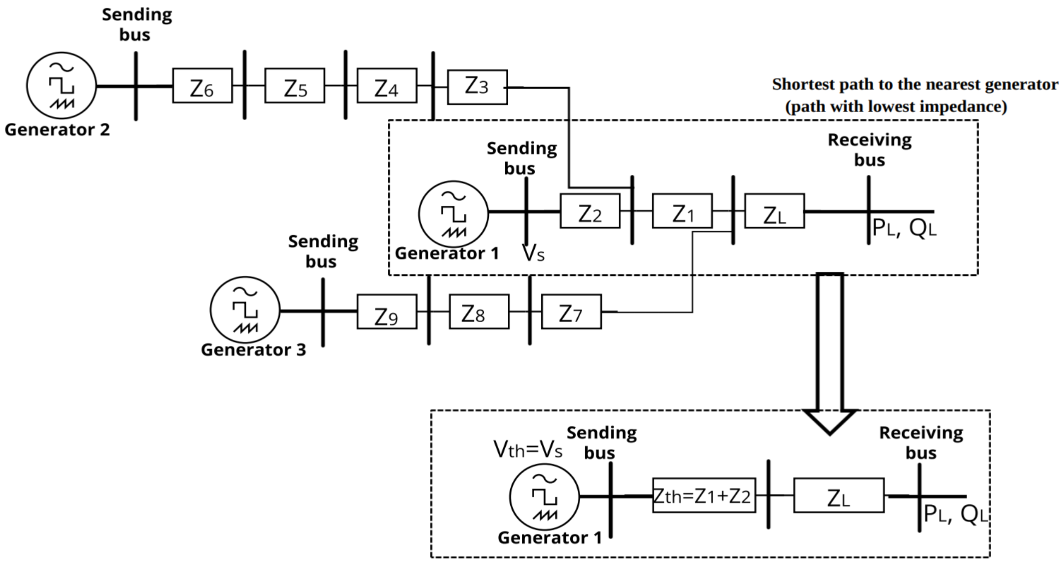


Figure 2. Illustration of the proposed method for determining the shortest path to the nearest generator

The $MLSI_{SP}$ values range from 0 to 1. Buses linked to lines where $MLSI_{SP}$ values are greater than unity are susceptible to experiencing a significant voltage decline leading to a voltage collapse.

## 4. SIMULATION TOOLS

### 4.1. Test Networks

To assess the proposed index's performance against the other indices mentioned in section two, IEEE 14-bus [15] and IEEE 30-bus [16] were selected as test networks. Slack bus, PV, and PQ buses distribution in each test network is shown below in Table 1.

Table 1. Buses distribution in the IEEE 14 and 30-bus networks

| | IEEE 14-bus | IEEE 30-bus | Known variables | Variables to be determined |
|---|---|---|---|---|
| Slack | 1 | 1 | $V, \delta$ | $P, Q$ |
| PV | 2,3,6,8 | 2,5,8,11,13 | $P, V$ | $Q, \delta$ |
| PQ | 4,5,7,9,10 ,11, 12,13,14 | Other buses | $P, Q$ | $V, \delta$ |

### 4.2. Simulation Methodology

Among the fundamental parameters to be used for the evaluation of the performance of an index are its sensitivity to an increase in the reactive and active load in the network and its effectiveness in predicting the system's voltage collapse when the line is disconnected. To do this, $MLSI_{SP}$ performance is evaluated based on the methodology described in the following steps:

- Step 1: Entering Bus and Line data for each network in MATLAB,
- Step 2: Execution of the Load flow using the Newton-Raphson technique,
- Step 3: Identification of weakest buses and lines,
- Step 4: Identification for each fragile line the shortest path to the nearest generator,
- Step 4: Calculation of Indices in the base case,
- Step 5: Sensitivity assessment of indices to active and reactive load,
- Step 6: Contingency analysis:
- Basic load with line outage,
- High reactive load with line outage,
- High active load with line outage.

## 5. RESULTS AND DISCUSSION

### 5.1. Identification of Fragile Lines

The first step is dedicated to the identification of the buses as well as the most fragile lines in the two test networks chosen previously. This step allows locating the areas that have a low stability margin of reactive and active load. To do this, a partial stability margin of the reactive (active) load of each bus "$n$" in the test networks is determined. This is done by increasing the active (reactive) load of bus "$n$" until the load flow calculation diverges while keeping the reactive and active loads of the other buses at their nominal (or base) values. Figures 3 and 4 show the partial active and reactive power stability margins in the IEEE 14 and 30-bus networks respectively.

Among all the buses in the IEEE 14-bus network, buses 10, 12, and 14 have the lowest partial stability margins in reactive and active powers. Bus 10 has partial stability margins of 2.4692 pu and 1.7588 pu in terms of active and reactive power. Bus 12 has an active partial margin of 2.0433 pu and a reactive partial margin of 1.7492 pu. Finally, bus 14 has very small partial margins: 1.4781 pu (Active) and 1.1434 pu (Reactive).

Regarding the IEEE 30 bus test network, buses 26, 29, and 30 are identified as the most fragile buses in the network. Indeed, bus 26 has 0.387 pu in active power and 0.3087 pu in reactive power. Bus 29 has an active partial margin of 0.5051 pu and a reactive partial margin of 0.3755 pu. Finally, bus 30 is the most fragile with very small partial margins: 0.4178 pu (Active) and 0.3319 pu (Reactive).

Based on these results, the fragile area for the studied network IEEE 14 bus, consists of buses 10, 12, and 14 and all lines connected to these buses, namely:

- Lines 11-10, 10-9 for bus 10,
- Lines 6-12, 12-13 for bus 12,
- Lines 9-14 and 13-14 for bus 14.

For IEEE 30 bus network, the weak area consists of buses 26, 29, and 30. The weak lines connected to these buses are the following:

- Line 25-26 for bus 26,
- Lines 27-29, 29-30 for bus 29,
- Lines 29-30 and 27-30 for bus 30.

For the rest of the document, the lines chosen for the simulation are lines 11-10, 6-12, and 13-14 of the IEEE 14-bus networks. And lines 25-26, 27-29, and 27-30 of the IEEE 30-bus networks.

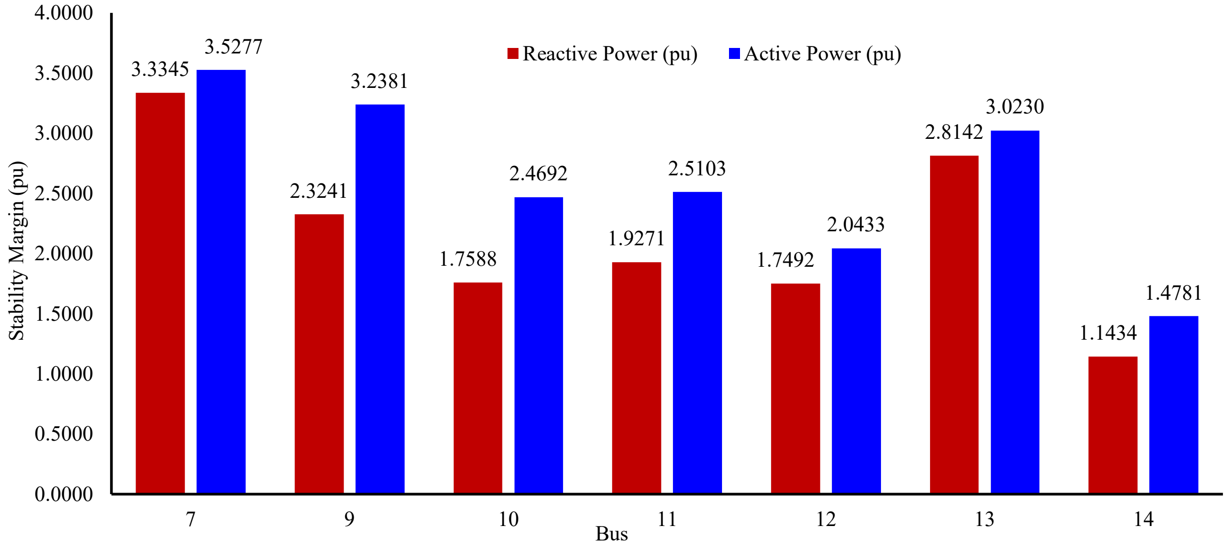


Figure 3. Partial stability margins of PQ buses - IEEE 14-bus network

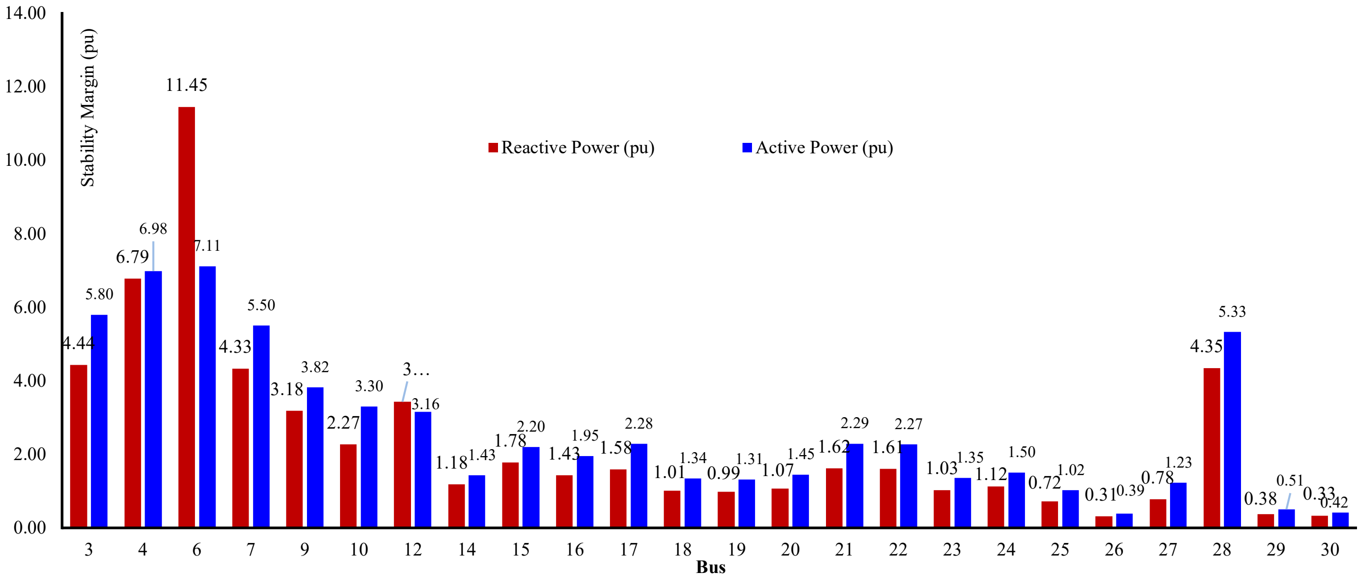


Figure 4. Partial stability margins of PQ buses - IEEE 30-bus network

## 5.2. Identification of Short Path for Fragile Lines

Based mainly on the procedure depicted in Figure 2, the shortest paths to the nearest generator for the fragile lines selected at the end of Section 5.1 was identified. These line connections include 11-10, 6-12, 13-14, 25-26, 27-29, and 27-30. The determined shortest paths for these connections are presented in Figures 5 and 6. It should be noted that within the IEEE 14-bus network, generator 6 is the closest generator to the three sending buses, namely buses 11, 6, and 13. For the IEEE 30-bus network, generator 8 is the closest generator for sending buses 25 and 27.

## 5.2. Basic Case

This second step is devoted to the evaluation of the indices in the base case. Line stability indices for the most fragile lines determined in the first step are computed. This calculation is performed in the base case where the load at each bus takes the specified value in the IEEE 14 and 30-bus network definition.

The results are reported in Tables 2 and 3. The analysis of two tables leads to the results as follows.

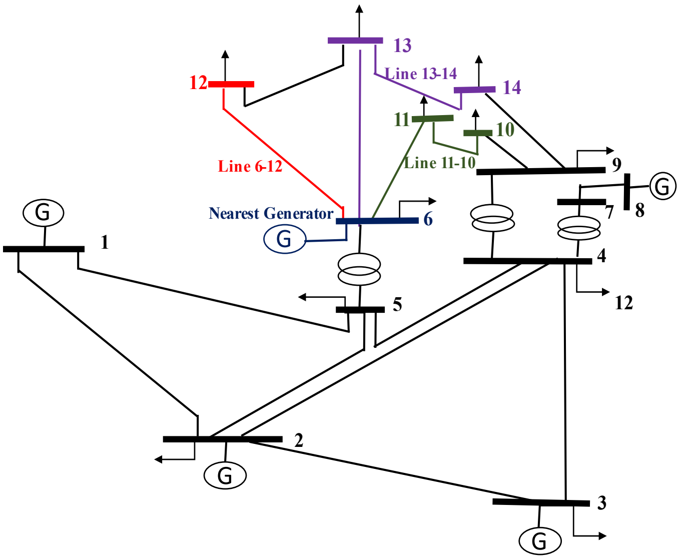


Figure 5. The shortest paths from lines 11-10, 6-12, and 13-14 to the nearest generator in IEEE 14-bus

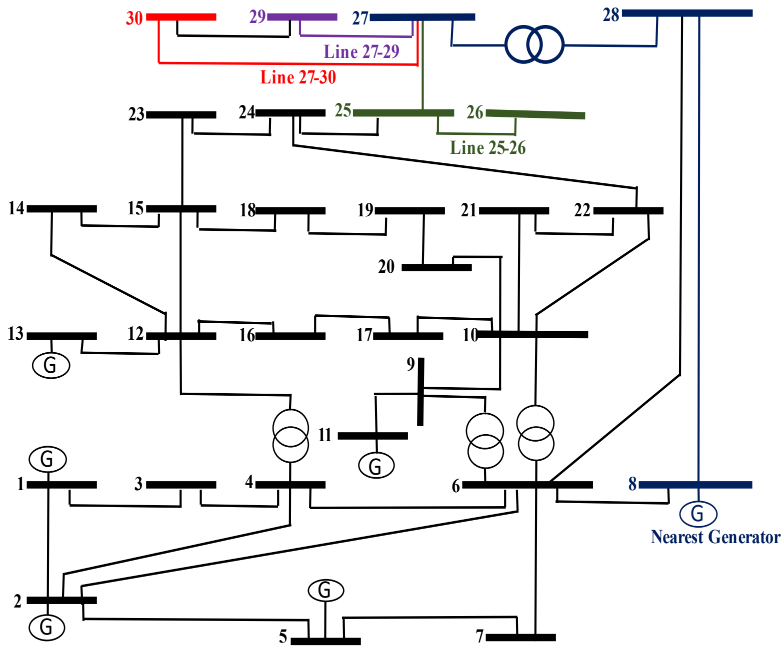


Figure 6. The shortest paths from lines 25-26, 27-29, and 27-30 to the nearest generator in IEEE 30-bus

Table 2. Line indices of fragile zone in IEEE 14-bus network-Base case

| Bus | Line | $MLSI_{SP}$ | $FVSI$ | $L_{mn}$ | $LQP$ | $LPP$ | $NLSI$ |
|---|---|---|---|---|---|---|---|
| 10 | 11-10 | 0.0621 | 0.0505 | 0.0506 | 0.0429 | 0.0136 | 0.0562 |
| 12 | 6-12 | 0.0629 | 0.0322 | 0.0327 | 0.0274 | 0.0342 | 0.0603 |
| 14 | 13-14 | 0.0958 | 0.0705 | 0.0714 | 0.0584 | 0.0392 | 0.0958 |

Table 3. Line indices of fragile zone in IEEE 30-bus Network-Base case

| Bus | Line | $MLSI_{SP}$ | $FVSI$ | $L_{mn}$ | $LQP$ | $LPP$ | $NLSI$ |
|---|---|---|---|---|---|---|---|
| 26 | 25-26 | 0.0811 | 0.0504 | 0.0509 | 0.0355 | 0.0356 | 0.0702 |
| 29 | 27-29 | 0.0793 | 0.0312 | 0.0319 | 0.0268 | 0.0522 | 0.0765 |
| 30 | 27-30 | 0.1228 | 0.0408 | 0.0425 | 0.0387 | 0.0864 | 0.1182 |

- For all the studied lines of the two IEEE 14 and 30-bus networks, the considered indices are very far from their critical value, in other words, the stability margin of the studied network is very important;
- For the IEEE 14-bus network, all indices indicate that line 13-14 is the most stressed, compared to the other lines;
- Except for $FVSI$ and $L_{mn}$, the other indices show that the critical line within the IEEE 30-bus is line 27-30. $FVSI$ and $L_{mn}$, which indicate that line 25-26 is the most fragile.

### 5.3. Sensitivity Analysis

An index must have acceptable sensitivity to any change in active and reactive load to qualify as reliable. In the present study, the suggested index's performance versus the indices mentioned in section two and towards the increase in active and reactive load has been evaluated. The two most stressed lines that were identified in the second step namely lines 13-14 and 27-30 for the networks IEEE 14 and 30-bus, respectively have been chosen for this study.

### 5.3.1. Reactive Power Variation

For an increase in reactive load, the two curves presented in Figure 7 have been found.

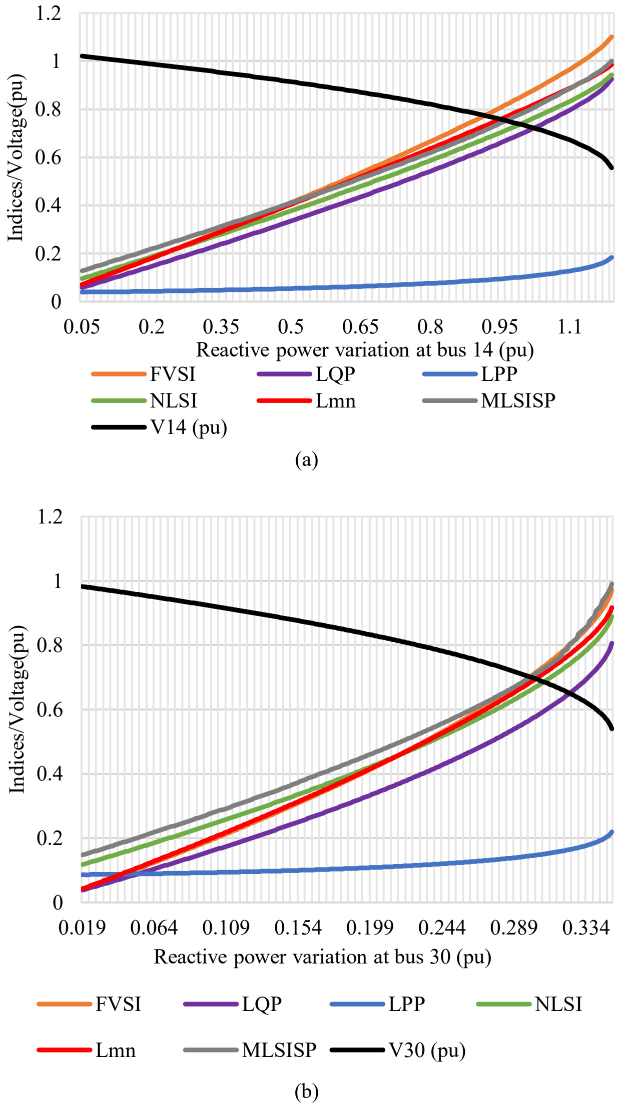


Figure 7. Indices evolution with reactive power, (a) at IEEE 14-bus, (b) at IEEE 30-bus

Based on Figure 7, it is evident that all indices, except *LPP*, are sensitive to the reactive load increase. $MLSI_{SP}$, *FVSI*, $L_{mn}$, and *NLSI* demonstrate the highest values, particularly at the loading limit. Specifically, $MLSI_{SP}$ and $L_{mn}$ reach their critical values ($MLSI_{SP}$=0.9998, $L_{mn}$=0.9851) for the IEEE 14-bus network, and the values ($MLSI_{SP}$=0.9908, $L_{mn}$ =0.9175) in the case of IEEE 30-bus systems. Whereas FVSI surpassed the critical value for the IEEE 14-bus network. That presents one of FVSI's major challenges, as it provides misleading information suggesting that the maximum load ability has already been reached, despite load flow convergence is still possible. These results confirm that $MLSI_{SP}$ accurately predicts the behavior of both systems toward increasing reactive load. Therefore, the $MLSI_{SP}$ has effectively showcased its superiority in monitoring reactive loads.

### 5.3.2. Active Power Variation

The voltage stability indices variation with increasing active load is illustrated in Figure 7.

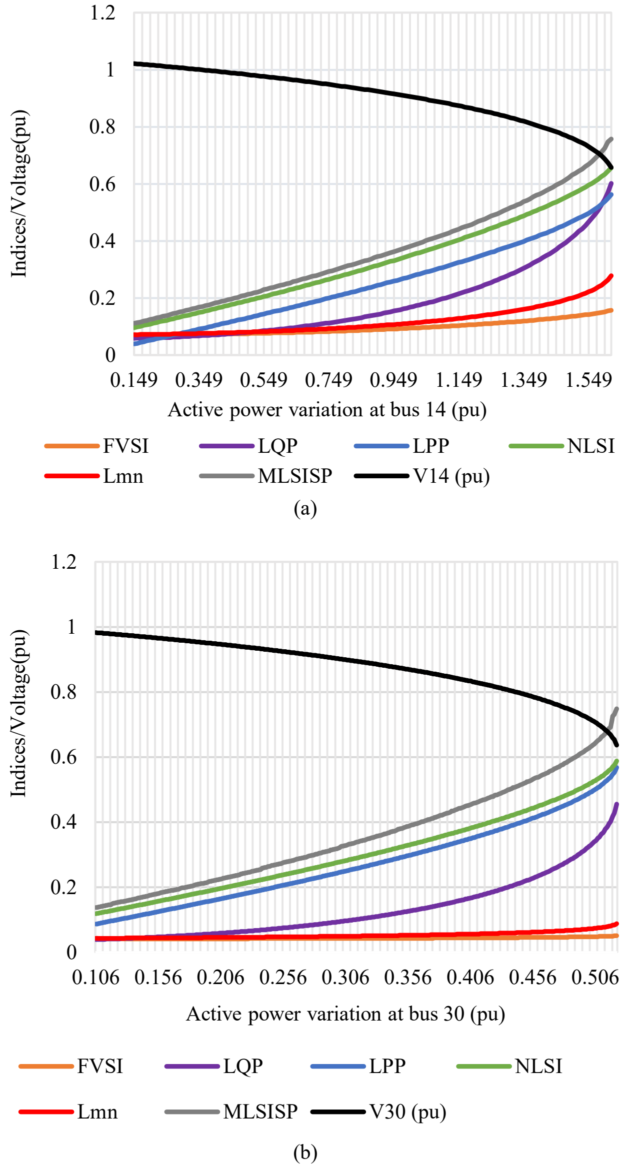


Figure 8. Evolution of indices with active power, (a) at IEEE 14-bus, (b) at IEEE 30-bus

Following the increase of active power, $MLSI_{SP}$ always shows high sensitivity and takes the highest values compared to the other indices. Initially starting with low values of 0.1113 and 0.1372 for the IEEE 14 and 30-bus networks respectively, $MLSI_{SP}$ rises the critical value of 0.7571 for an active load of 1.619 and the critical value of 0.7483 for an active load of 0.523. On the other hand, *NLSI*, *LPP*, and *LQP* indices vary moderately with active power, and their variation always remains below the $MLSI_{SP}$ range. However, *FVSI* and $L_{mn}$ vary insensitively with active power. Hence, $MLSI_{SP}$ has successfully demonstrated its superiority in terms of active load surveillance.

## 5.4. Contingency Analysis

To evaluate the efficiency of the index $MLSI_{SP}$ in predicting voltage collapse after a line outage in the network, an analysis of contingency is carried out under base load, high reactive load, and high active load conditions. The buses chosen for this study are the most fragile ones as identified in the first part of section 5. Specifically, for the IEEE 14-bus network, buses 10, 12, and 14 were chosen. Similarly, for IEEE 30-bus system, the selected buses are 26, 29, and 30.

### 5.4.1. Case 1: Line Outage with a Basic Load

The principle of this case is based on increasing the active (reactive) load in one of the specific buses until the load flow schedule diverges. After the load flow divergence, the reactive and active power stability margins and the line index values are recorded. The same process is repeated after a line break. The main results obtained are reported in the Tables 4 and 5.

Table 4. Pre and post contingency indices values for the IEEE 14-bus network - Base case

| Case | Disconnected line | Reactive/active load margin(p.u.) | Line | $MLSI_{SP}$ | $FVSI$ | $L_{mn}$ | $LQP$ | $LPP$ | $NLSI$ |
|---|---|---|---|---|---|---|---|---|---|
| Basic case | - | $\Delta Q_{10}$=1.7588 / $\Delta P_{10}$=2.4692 | 11-10 | 0.0562 | 0.0505 | 0.0506 | 0.0429 | 0.0136 | 0.0562 |
| | | $\Delta Q_{12}$=1.7492 / $\Delta P_{12}$=2.0433 | 6-12 | 0.0603 | 0.0322 | 0.0327 | 0.0274 | 0.0342 | 0.0603 |
| | | $\Delta Q_{14}$=1.1434 / $\Delta P_{14}$=1.4781 | 13-14 | 0.0958 | 0.0705 | 0.0714 | 0.0584 | 0.0392 | 0.0958 |
| Line outage | 9-10 | $\Delta Q_{10}$=0.6065 / $\Delta P_{10}$=0.7984 | 11-10 | 0.5199 | 0.3689 | 0.4081 | 0.3490 | 0.2720 | 0.5103 |
| | 12-13 | $\Delta Q_{12}$=1.03 / $\Delta P_{12}$=1.3363 | 6-12 | 0.4903 | 0.2429 | 0.2642 | 0.2853 | 0.2245 | 0.3692 |
| | 9-14 | $\Delta Q_{14}$=0.4853 / $\Delta P_{14}$=0.5761 | 13-14 | 0.5595 | 0.3806 | 0.4146 | 0.4193 | 0.4233 | 0.5110 |

Table 5. Pre and post contingency indices values for the IEEE 30-bus network - Base case

| Case | Disconnected line | Reactive/active load margin(p.u.) | Line | $MLSI_{SP}$ | $FVSI$ | $L_{mn}$ | $LQP$ | $LPP$ | $NLSI$ |
|---|---|---|---|---|---|---|---|---|---|
| Basic case | - | $\Delta Q_{25}$=0.7234 / $\Delta P_{25}$=1.0197 | 25-26 | 0.0178 | 0.0071 | 0.0071 | 0.0055 | 0.0124 | 0.0178 |
| | | $\Delta Q_{29}$=0.3755 / $\Delta P_{29}$=0.5051 | 27-29 | 0.0765 | 0.0312 | 0.0319 | 0.0268 | 0.0522 | 0.0765 |
| | | $\Delta Q_{30}$=0.3319 / $\Delta P_{30}$=0.4178 | 27-30 | 0.1182 | 0.0408 | 0.0425 | 0.0387 | 0.0864 | 0.1181 |
| Line outage | 27-25 | $\Delta Q_{25}$=0.3601 / $\Delta P_{25}$=0.4565 | 25-26 | 0.5598 | 0.4428 | 0.4431 | 0.4328 | 0.4277 | 0.5508 |
| | 29-30 | $\Delta Q_{29}$=0.3262 / $\Delta P_{29}$=0.4462 | 27-29 | 0.4651 | 0.4186 | 0.4218 | 0.4149 | 0.4006 | 0.4233 |
| | 29-30 | $\Delta Q_{30}$=0.226 / $\Delta P_{30}$=0.2652 | 27-30 | 0.6571 | 0.5723 | 0.5812 | 0.5613 | 0.6025 | 0.6176 |

The following remarks are made from the analysis of the last two tables:

- In the base case and since all lines are connected, the indices take their base values as shown in Tables 2 and 3;
- Both tables confirm that disconnecting a line decreases power system stability margins and significantly increases voltage stability indices;
- The loss of line 9-14 and 29-30 can be considered the most critical case for the network IEEE 14 and 30-bus respectively since lines 13-14 and 27-30 have the highest index values;
- For both networks, the proposed index $MLSI_{SP}$ registered the highest values compared to the other indices. Namely the value of 0.5595 for line 13-14 and 0.6571 for line 27-30.

To summarize, the initial contingency analysis highlights notable fluctuations in all indices following the opening of a line. Among the indices examined, the $MLSI_{SP}$ demonstrates the greatest sensitivity when compared to other indices.

### 5.4.2. Case 2: Line Outage with a High Reactive Load

The second case was used to evaluate the effect of the loss of a line with a high reactive load on the indices. Tables 6 and 7 show the different values of the indices after line outage and changing the reactive load in each bus.

Table 6. Indices values after high reactive load combined with line loss for the IEEE 14-bus network

| Disconnected line | Reactive load (p.u.) | Reactive load margin | Line | $MLSI_{SP}$ | $FVSI$ | $L_{mn}$ | $LQP$ | $LPP$ | $NLSI$ |
|---|---|---|---|---|---|---|---|---|---|
| 9-10 | $Q_{10}$=0.6065 | $\Delta Q_{10}$=0 (Critical case) | 11-10 | 0.9507 | 0.9585 | 0.8977 | 0.8279 | 0.1094 | 0.8575 |
| 12-13 | $Q_{12}$=1.03 | $\Delta Q_{12}$=0 (Critical case) | 6-12 | 0.9894 | 1.1507 | 0.9778 | 0.9870 | 0.2074 | 0.8910 |
| 9-14 | $Q_{14}$=0.4853 | $\Delta Q_{14}$=0 (Critical case) | 13-14 | 0.9941 | 1.0603 | 0.9884 | 0.9248 | 0.2438 | 0.9710 |

Table 7. Indices values after high reactive load combined with line loss for the IEEE 30-bus network

| Disconnected line | Reactive load (p.u.) | Reactive load margin | Line | $MLSI_{SP}$ | $FVSI$ | $L_{mn}$ | $LQP$ | $LPP$ | $NLSI$ |
|---|---|---|---|---|---|---|---|---|---|
| 25-27 | $Q_{25}$=0.3601 | $\Delta Q_{25}$=0 (Critical case) | 25-26 | 0.9825 | 1.0983 | 0.9510 | 0.8509 | 0.1689 | 0.8724 |
| 29-30 | $Q_{29}$=0.3262 | $\Delta Q_{29}$=0 (Critical case) | 27-29 | 0.9643 | 1.0905 | 0.9555 | 0.8731 | 0.1484 | 0.8841 |
| 29-30 | $Q_{30}$=0.226 | $\Delta Q_{30}$=0 (Critical case) | 27-30 | 0.9989 | 0.9993 | 0.9671 | 0.8701 | 0.2946 | 0.9584 |

As shown in both Tables 6 and 7, disconnecting a line with a high reactive load in each specific bus leads the stability margin to the critical case. As a result, the indices increase markedly for the lines connected to the bus subject to the disturbance. It has been noted also, that $MLSI_{SP}$ and $L_{mn}$ are the closest to unity when compared with $NLSI$, $LQP$, and $LPP$. This can be observed for lines 6-12, 13-14, and 27-30 when the reactive load of buses 12, 14, and 30 is set within the stability limit $Q_{12}$=1.03 pu, $Q_{14}$=0.4853 pu, and $Q_{30}$=0.226 pu, respectively. While the $FVSI$ exceeds unity for lines 6-12, 13-14, 25-26, and 27-29. This discrepancy presents a significant drawback for $FVSI$, as it falsely indicates the system has reached its maximum reactive load capacity, even though this is not the actual scenario. Consequently, the *FVSI* index can lead to incorrect assessments of the system's load ability and may result in sub-optimal decision-making in power system operations. Furthermore, the *LPP* is relatively insensitive to this disturbance, representing low values far from the critical value, such as 0.1094 and 0.1689 for lines 11-10 and 25-26. This finding serves to validate the heightened sensitivity of the $MLSI_{SP}$ following the presence of a large reactive load and simultaneous line loss.

### 5.4.3. Case 3: Line Outage with a High Active Load

A contingency analysis with high active load is performed for both IEEE 14 and 30-bus networks. The following tables provide a summary of the findings.

Table 8. Indices values after high active load combined with line loss for the IEEE 14-bus network

| Disconnected line | Active load (p.u.) | Active load margin | Line | $MLSI_{SP}$ | *FVSI* | $L_{mn}$ | *LQP* | *LPP* | *NLSI* |
|---|---|---|---|---|---|---|---|---|---|
| 9-10 | $P_{10}$=0.7984 | $\Delta P_{10}$=0 (Critical case) | 11-10 | 0.8620 | 0.3906 | 0.4254 | 0.4641 | 0.4649 | 0.6208 |
| 12-13 | $P_{12}$=1.3363 | $\Delta P_{12}$=0 (Critical case) | 6-12 | 0.8915 | 0.2598 | 0.2652 | 0.6094 | 0.6733 | 0.6143 |
| 9-14 | $P_{14}$=0.5761 | $\Delta P_{14}$=0 (Critical case) | 13-14 | 0.9262 | 0.3779 | 0.4181 | 0.6852 | 0.6181 | 0.6519 |

Table 9. Indices values after high active load combined with line loss for the IEEE 30-bus network

| Disconnected line | Active load (p.u.) | Active load margin | Line | $MLSI_{SP}$ | *FVSI* | $L_{mn}$ | *LQP* | *LPP* | *NLSI* |
|---|---|---|---|---|---|---|---|---|---|
| 25-27 | $P_{25}$=0.4565 | $\Delta P_{25}$=0 (Critical case) | 25-26 | 0.8716 | 0.4498 | 0.4499 | 0.4710 | 0.6040 | 0.6415 |
| 29-30 | $P_{29}$=0.4462 | $\Delta P_{29}$=0 (Critical case) | 27-29 | 0.8364 | 0.4198 | 0.4278 | 0.4909 | 0.5941 | 0.6315 |
| 29-30 | $P_{30}$=0.2652 | $\Delta P_{30}$=0 (Critical case) | 27-30 | 0.9063 | 0.5774 | 0.5812 | 0.5988 | 0.6285 | 0.6577 |

The $MLSI_{SP}$ index remains consistently high for both test networks. Specifically, when buses 14 and 30 are loaded to their maximum active power ($P_{14}$=0.5761 pu, $P_{30}$=0.2652) and lines 9-14 and 29-30 are unconnected, the $MLSI_{SP}$ values for lines 13-14 and 27-30 reach 0.9262 and 0.9063 respectively. This indicates a significant increase of 0.8304 and 0.7881 compared to the baseline load without line loss. However, the *FVSI*, $L_{mn}$, *LPP*, *LQP*, and *NLSI* indices show minimal variation with this disturbance and deviate significantly from unity. This result again confirms the high sensitivity of $MLSI_{SP}$ after a high active load combined with line loss.

## 6. CONCLUSION

A modified line stability index called $MLSI_{SP}$ for assessing voltage stability has been introduced in this paper. It is mainly based on the shortest path to the nearest generator method. It takes into account the transport angle in the line, the line parameters (*X* and *R*), and both reactive and active power. Therefore, it can provide more reliable results compared to other indices. The suggested index's reliability has been properly analyzed and compared to other existing indices. The findings of its application to IEEE 14 and 30 bus test networks, under basic and high disturbance cases, have shown that the proposed index demonstrates its ability to accurately predict the proximity of voltage collapse. The index can be applied to classify lines in order of criticality and also to predict the active and reactive stability margin in the case of basic and high disturbances. Near the voltage collapse point (critical point), the $MLSI_{SP}$ value approaches unity, while other indices such as $L_{mn}$, *FVSI*, *NLSI*, *LQP*, and *LPP* do not provide a true assessment of the voltage stability, especially after a high active load combined with line loss. The sensitivity of the recommended index towards active and reactive power has also been evaluated and showed its superiority for the two studied networks.

## NOMENCLATURE

### 1. Symbol / Parameters

$P_s$, $P_r$: Active power on the sending and receiving buses
$Q_s$, $Q_r$: Reactive power on the sending and receiving buses
$S_s$, $S_r$: Apparent power on the sending and receiving buses
$V_s$, $V_r$: Voltage magnitude on the sending and receiving buses
$\delta$, $\delta_s$, $\delta_r$: The voltage angle difference, the voltage angle of the sending and receiving buses, respectively
$\theta$: Line impedance angle
*R*, *X*, *Z*: Line resistance, line reactance, and line impedance.

## REFERENCES

[1] A.M. Hashimov, N.R. Rahmanov, N.M. Tabatabaei, H.B. Guliyev, F.S. Ibrahimov, "Probabilistic Evaluation of Voltage Stability Limit of Power System under the Conditions of Accidental Emergency Outages of Lines and Generators", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 43, Vol. 12, No. 2, pp. 40-45, June 2020.
[2] R. Gadal, F. Elmariami, A. Oukennou, N. Agouzoul, A. Tarraq, "An Assessment of Line Voltage Stability Indices to Select the Best Combination for Voltage Stability Prediction", Proc. Int. Conf. Electr. Syst. Autom., pp. 93-103, 2022.
[3] A. Cheraghi Valujerdi, M. Mohammadian, "A Novel Load Shedding Method to Improve Transmission Line Performance and Voltage Stability Margin", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 13, Vol. 4, No. 4, pp. 110-118, December 2012.
[4] S. Mokred, Y. Wang, T. Chen, "Modern Voltage Stability Index for Prediction of Voltage Collapse and Estimation of Maximum Load-Ability for Weak Buses and Critical Lines Identification", Int. J. Electr. Power Energy Syst., Vol. 145, No. 108596, pp. 1-19, 2022.
[5] R.A. Moradi, R. Zeinali Davarani, "Introducing a New Index to Investigate Voltage Stability of Power Systems

under Actual Operating Conditions", Int. J. Electr. Power Energy Syst., Vol. 136, No. 107637, pp. 1-7, 2021.
[6] B. Ismail, et al., "New Line Voltage Stability Index (BVSI) for Voltage Stability Assessment in Power System: The Comparative Studies", IEEE Access, Vol. 10, No. 3204792, pp. 103906-103931, 2022.
[7] M.S.S. Danish, T. Senjyu, S.M.S. Danish, N.R. Sabory, K. Narayanan, P. Mandal, "A Recap of Voltage Stability Indices in the Past Three Decades", Energies, pp. 1-18, 2019.
[8] R. Gadal, F. Elmariami, A. Oukennou, N. Agouzoul, A. Tarraq, "An Assessment of Line Voltage Stability Indices to Select the Best Combination for Voltage Stability Prediction", The Proceedings of the International Conference on Electrical Systems and Automation, pp. 93-103, 2022.
[9] A. Oukennou, "Contribution to the Development of Voltage Stability Indicators and their Use in the Search for the Optimal Location of FACTS in Electrical Networks", Journal of Electrical and Computer Engineering, Casablanca, Morocco, 2021.
[10] S. Yari, H. Khoshkhoo, "A Comprehensive Assessment to Propose an Improved Line Stability Index", Int. Trans Electr. Energ. Syst., Vol. 29, No. 4, pp. 1-25, 2019.
[11] I. Musirin, T.K.A. Rahman, "Estimating Maximum Load Ability for Weak Bus Identification Using FVSI", IEEE Power Eng. Rev., Vol. 22, No. 11, pp. 50-52, 2002.
[12] M. Moghavvemi, F.M. Omar, "Technique for Contingency Monitoring and Voltage Collapse Prediction", IEE Proc. Gener. Transm. Distrib., Vol. 145, No. 6, pp. 634-640, 1998.
[13] S.Y.A. Mohamed, G.B Jasmon, "A Static Voltage Collapse Indicator Using Line Stability Factors", J. Ind. Technol., Vol. 7, No. 1, pp. 73-85, 1989.
[14] A. Yazdanpanah Goharrizi, R. Asghari, "A Novel Line Stability Index (NLSI) for Voltage Stability Assessment of Power Systems", The 7th WSEAS International Conference on Power Systems, pp. 164-167, 2007.
[15] J.A. Boudreaux, "Design, Simulation, and Construction of an IEEE 14-Bus Power System", Masters Thesis, Louisiana State University and Agricultural and Mechanical College, September 2018.
[16] H. Saadat, "Power System Analysis", McGraw Hill Inc., Chapter 6, Example 6.9, 1998.

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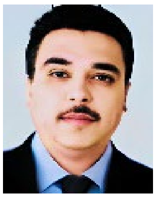

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