A Missing Data Tolerant Wide-Area Back-Up Protection Scheme for Transmission Network

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ABSTRACT The proposed scheme develops a missing data tolerant wide area back-up protection scheme for power transmission network with fewer PMUs. The scheme assumes division of power system into different coherent groups. The fault detection index (FDI) is used to detect a fault in the system network using active power transfer and angular difference between voltages of connected areas or summation of negative and zero sequence current components in each area. The faulted area is then identified by change in area-current (CAC) using current contribution towards each area and finally, the faulted line is identified for the respective faulted area using distance to fault (DF) index. The scheme is extensively tested on a New-England 39-bus system for several fault and stressed scenarios considering all PMU data available and PMU data loss at some of the buses. For this, the PMUs are deployed at less than half number of system buses. The maximum response time of the proposed scheme is approximately 260 ms which is well within the third zone operation time of distance relays for back-up protection. The test results including the comparative assessment with existing schemes indicate that the proposed scheme can be a potential candidate for enhancing the performance of the wide-area back-up protection in the transmission network.

INDEX TERMS Wide-area measurement systems (WAMs), phasor measurement unit (PMU), data loss, missing data communication failure, faulted line identification.

I. INTRODUCTION

With the growth of PMU technology for WAMs applications, wide- area based protection schemes have gained significant momentum [1]. Moreover, the incapability of traditional distance relay-based back-up protection in dealing with issues such as stable power swing, load encroachment, and voltage stressed condition have given more impetus to the development of PMU based wide-area transmission network protection schemes. This is required to overcome the detrimental effects of relay maloperation due to stressed conditions on power system [2], [3], [4]. PMU provides synchronized phasor information from instantaneous voltage and currents, which is timed tagged with GPS clock [5]. Many wide-area back-up protection schemes for faulted line identification (FLI) employ PMUs at the network buses to perform their task. Paper [6] has used positive sequence voltage magnitude at the buses for finding out the faulted bus and current angle difference for the lines connected to the faulted bus to further find out the faulted line. Eissa et al. [7] used sequence voltage magnitudes to find the faulted bus for symmetrical and unsymmetrical faults. The faulted line adjacent to the faulted bus was identified using the phase angle between current and voltage at the ends of the adjacent lines. A current differential protection scheme for identifying the faulted line by eliminating the error arising due to shunt capacitances was proposed in [8]. Faulted line for series compensated line was found using phase angle of positive sequence integrated impedance (PAPSII) in [9]. In [10], a global comparison between apparent impedances derived from cRIO based PMUs was performed to distinguish fault from load encroachment. In [11], a composite impedance
directional principle was used for fault detection and faulty phase identification. First of all, the composite impedances were calculated using single end voltage information and differential current information for the lines. The faulted branch was identified using imaginary part and phase angle of composite impedance. Online intelligent based techniques utilizing were proposed to distinguish fault from stressed conditions [12], [13]. The phasor information from single end and differential information from buses were formed as classifiers for segregating stressed system conditions from fault. The above schemes have utilized PMU information at all the network buses connecting lines. Though the schemes utilizing PMU information at all the buses are quite effective, it adds to huge implementation cost. Moreover, larger PMU usage with huge data sharing leads to more end-to-end latencies and data congestion at the Phasor Data Concentrator (PDC) end.

Few schemes have been developed for FLI with fewer PMUs. In [14], voltages at non-PMU buses were calculated from dissimilar paths to find the faulted bus. The faulted line was then calculated for the lines connected to the faulted bus. For this, the PMUs were required at more than half number of system buses. In [15], the concept of a decentralized protection scheme was introduced, where, the power system is divided into different protection zones. Initially, the vulnerable protection zone (VPZ) was identified using gain in momentum. Further, voltage magnitude information derived from PMUs at the vulnerable buses inside the VPZ were used to find the faulted bus. Finally, the faulted line was identified using reactive power flow from the faulted bus. However, the study was not performed for voltage stressed conditions. Another scheme [16] utilized the centre of reactive power to find the probable faulted region (PFR) using generator terminal bus voltage data. The faulted line was identified inside the PFR using reactive power flow from the buses connected to the lines. However, this scheme required PMUs data at all the buses to identify the faulted line. A scheme utilizing PMU data at the relay bus and at the end of the adjacent lines connected to the protected line was used to address the effect of infeed currents and load encroachment for third zone operation is addressed in [17]. An algorithm based on Deep Neural Network based tool using PMU information was used for secure operation of power system under stressed conditions [18].

The aforementioned schemes rely on accurate and complete availability of PMU information at protection centres. However, in the event of missing data from PMU end due to malfunctioning PMU devices or communication failure, or similar reasons, the decision-making becomes challenging. Hence, addressing the reliability of the wide-area protection scheme during PMU data loss is mandated. Even though PMU has self-correcting capability, however, the situation cannot be completely eliminated. The inability of a protection scheme to detect a fault even due to the unavailability of data may aggravate the disturbance situation, leading to cascaded outages. In [19], a Wide Area Back-up Protection (WABP) scheme was developed which detected the fault and identified the faulted line with PMU data unavailability at critical buses. However, it considered the initial PMU placement at all the buses. Moreover, in order to find the faulted line, every bus with unavailable data should be adjacent to at least three other PMU buses.

To alleviate the aforementioned issues, a wide-area back-up protection scheme with enhanced performance is proposed with the following objectives:

1) It should be dependable for different fault events and secure for stressed conditions such as stable power swing, load encroachment, and voltage degraded conditions.

2) It aims at utilizing limited PMU information to perform the task of fault detection, faulted area identification and FLI.

3) The scheme aims at reliable operation even if there are PMU data losses at some point in time. The faulted area and faulted line identification are carried out only when a fault is detected in the system.

4) It aims to work effectively for measurement errors from PMUs.

The organization of the paper is as follows: Section II describes the proposed methodology. Section III includes the assessment of the proposed scheme for several faults and stressed conditions including the performance for PMU data loss and measurement errors and Section IV lists the comparison of the proposed scheme with existing schemes. Section V provides the conclusions of the paper.

II. PROPOSED METHODOLOGY
In order to target the faulted line, the proposed scheme comprises of three steps. In the first step, the fault condition is distinguished from the stressed condition. In the second step, the faulted area is identified and the last step is to find the faulted line within the faulted area. The concept of FLI with data unavailability from the PMUs is also taken into consideration.

A. FAULT DETECTION INDEX
This step is used for detecting a fault condition and thus, distinguishing the occurrence of the fault from other stressed conditions. Following a disturbance, a certain group of generators has a tendency to swing together, which falls under a coherent group. The entire power system is assumed to be divided into different areas which can be represented as an equivalent power system model [20], [21], [22], [23]. Various disturbance cases including single and multiple generators and line outages, and load switching over different operating scenarios are considered for coherent group classification. Considering, a two bus equivalent of a system network, the angular differences between voltages from areas A and B is given as

\[ \delta_{A-B} = \delta_A - \delta_B \] (1)

where, \( \delta_A = \frac{1}{n_A} \sum_{i=1}^{n_A} H_i \delta_i \) and \( \delta_B = \frac{1}{n_B} \sum_{j=1}^{n_B} H_j \delta_j \).

Since, the rotor angle cannot be obtained directly, it is computed using phasor information at the generator terminal...
buses [24]. The PMUs can be installed at the terminal bus of the generator to derive the rotor angle of the generator. Following a fault in the system, the active power (P) transfer from the generators in an area supplying the fault MVA reduces. For this, the angular difference between voltages of connected areas (δ) increases [25].

Hence, the index based on product of change in active power and angular difference between voltages (PCPA) is defined as,

$$\text{PCPA}_{n+3} = (P_{n+3} - P_n) \cdot (\delta_{n+3} - \delta_n)$$

(2)

where, n is the sample number such that the change is derived using data with current sample and three samples before. This is done to avoid index deviation from threshold due to switching transients or measurement errors. The PCPA for stressed condition is either positive or shows negligible deviation since the variation of active power is directly proportional to the angular difference between voltages of connected areas in normal situations. However, PCPA might have lower magnitude for high resistance unsymmetrical fault cases. To add to the dependability of the proposed scheme for unsymmetrical fault cases, the summation of negative and zero sequence current components from PMU buses in an area is utilized. A logical OR operation is assigned for detecting both symmetrical as well as unsymmetrical fault conditions. Thus, the fault detection index is defined here as,

$$FDI_{n+3} = \text{PCPA}_{n+3} \lor \sum_{k=1}^{N} |i_{(n+3)k2} + i_{(n+3)k0}|$$

(3)

for k=1 to N number of PMU buses in an area and $i_{(n+3)k2}$ and $i_{(n+3)k0}$ are the negative and zero sequence current components from PMU buses in an area. It is negligible for symmetrical fault or stressed conditions, while it shows a deviation for unsymmetrical fault cases.

The system is considered faulty if for any connected areas,

$$FDI_{n+3} < 0.$$
areas so that the power flow information between connected areas is available even after the loss of information from any one of the boundary buses. From Fig.1, it is observed that area A and B are connected with border buses N and N-3.

Hence, in the first step of the proposed scheme, the fault in the system is detected irrespective of the PMU data loss at any of the buses.

**B. FAULTED AREA IDENTIFICATION**

After the detection of fault in the network, the faulted area is identified to find the faulted line within the detected faulted area. This reduces the end to end latencies at the PDC end during line identification. For this, the sum of the positive sequence currents from the generator and boundary buses encompassing each area is calculated and taken into account after the fault detection step.

During fault, the contribution of the current towards a faulted area increases and the other areas reduces or has negligible deviation from pre-fault case. Hence, the faulted area is identified based on the change in currents from generator and boundary buses towards an area. Hence, for an area to be a faulted area the change in area-current (CAC) should verify the following equation,

\[
CAC = \left| \sum_{n=1}^{N_p} I_{post}^{n} \right| - \left| \sum_{n=1}^{N_p} I_{pre}^{n} \right| > 0.01 \times \left| \sum_{n=1}^{N_p} I_{pre}^{n} \right| \tag{7}
\]

where, \(I_{post}\) and \(I_{pre}\) are the post-fault and pre-fault positive sequence current samples derived from \(N_p\) number of PMUs at the generator buses and boundary buses surrounding an area. “0.01” is chosen by observing CAC values for far-end high resistance faults from boundary PMU buses in different areas.

**C. FAULTED LINE IDENTIFICATION (FLI)**

The task of FLI is carried out after identifying the faulted area using the algorithm described in section II (B). Considering, each area as a separate network, an impedance bus matrix for each area is formed. For forming the impedance matrix, the impedance for all the non-PMU load buses are calculated from pre-fault load current and voltage. This step is used to ensure the total current injection at non-PMU buses to be zero by Kirchhoff’s Current Law (KCL). For an area consisting of \(N\) number of buses with \(N_p\) PMU buses and \(N_n\) non-PMU buses, the matrix equation for a particular zone is given as,

\[
\begin{bmatrix}
V_1 \\
\vdots \\
V_{N_p} \\
V_{N_p+1} \\
\vdots \\
V_{N_p+N_n}
\end{bmatrix} =
\begin{bmatrix}
Z_{11} & \cdots & Z_{1N_p} & \cdots & Z_{1N_n} \\
\vdots & \ddots & \vdots & \ddots & \vdots \\
Z_{N_p1} & \cdots & Z_{N_pN_p} & \cdots & Z_{N_pN_n} \\
\vdots & \ddots & \vdots & \ddots & \vdots \\
Z_{N_n1} & \cdots & Z_{N_nN_p} & \cdots & Z_{N_nN_n}
\end{bmatrix}
\begin{bmatrix}
I_1 \\
\vdots \\
I_{N_p} \\
I_{N_p+1} \\
\vdots \\
I_{N_p+N_n}
\end{bmatrix}
\tag{8}
\]

where, \(V_1\) to \(V_{N_p}\) are the voltages of the required PMU buses and \(V_{N_p+1}\) to \(V_{N_p+N_n}\) are the voltages of non-PMU buses. \(I_1\) to \(I_{N_p}\) are the currents from all the PMU buses towards the area. To identify the faulted line, voltage and currents from the buses corresponding to the lines are required. For this, each line inside a faulty network is assumed to be removed. For example: suppose a line of impedance \(z_{pq}\) is removed. This implies the addition of \(-z_{pq}\) to the network. The new network impedance is obtained by using \(Z_{bus}\) modification described in [26].

\[
Z_{New} = Z_{old} - \frac{1}{-z_{pq} + Z_{pp} + Z_{qq} - 2Z_{pq}ZZ^T} \tag{9}
\]

where,

\[
Z =
\begin{bmatrix}
Z_{1p} - Z_{1q} \\
\vdots \\
Z_{N_p} - Z_{N_p}\ (p) \\
\vdots \\
Z_{N_n} & - Z_{N_n}\ (q)
\end{bmatrix}
\]

The voltages and currents at all the PMU buses are known. Moreover, except the currents from the buses corresponding to the line which is assumed to be removed, current injections at all the non-PMU buses are zero.
Ibuses in an area, say due to the formation of bus-impedance matrix. If both p and q are equipped with PMU, this can be calculated directly using the PMU phasors. If a line consists of one lines within the faulted area, the area identification should lie between 0 and 1. For the other unknown phasors are,\[ X = V_i - \sum_{k=1}^{N_p} Z_{New} (i, k) \times I_k \] (11)
and\[ Y = V_j - \sum_{k=1}^{N_p} Z_{New} (j, k) \times I_k \text{ for } i \neq j \] (12)

Now,\[ -X = I_{pq} Z_{New} (i, p) + I_{qp} Z_{New} (i, q) \] (13)
\[ -Y = I_{pq} Z_{New} (j, p) + I_{qp} Z_{New} (j, q) \] (14)

Solving equations (13) and (14) yields the unknown currents \( I_{pq} \) and \( I_{qp} \). Hence, the unknown voltages \( V_p \) and \( V_q \) are calculated from the \( p^{th} \) and \( q^{th} \) rows of new bus impedance matrix with PMU derived currents and calculated current through lines p-q. Using the calculated values for voltages and currents for each lines, the faulted line is identified using distance to fault (DF).

\[ DF = \frac{V_p - V_q + I_{qp} z_{pq}}{(I_{pq} + I_{qp}) z_{pq}} \] (15)

For a faulted line, the value of DF considered after fault area identification should lie between 0 and 1. For the other lines within the faulted area, the DF is beyond this range. If both p and q are equipped with PMU, this can be calculated directly using the PMU phasors. If a line consists of one PMU and one non-PMU bus, the unknown current can be solved using any one of the equations (13) or (14). Hence, the computational burden to find the faulted line is reduced due to the formation of bus-impedance matrix.

Suppose, data becomes unavailable at any of the PMU buses in an area, say \( I_l = 0 \). Equations (13) and (14) are modified, and an additional equation is included considering the unknown current from PMU bus, \( I_{l,calc} \). For this, each closed area should have at least three known voltage phasors from PMUs. Hence, the new system of equations to get the unknown phasors are,
\[ -X = I_{pq} Z_{New} (i, p) + I_{qp} Z_{New} (i, q) + I_{l,calc} Z_{New} (i, l) \] (16)
\[ -Y = I_{pq} Z_{New} (j, p) + I_{qp} Z_{New} (j, q) + I_{l,calc} Z_{New} (j, l) \] (17)
\[ -Z = I_{pq} Z_{New} (m, p) + I_{qp} Z_{New} (m, q) + I_{l,calc} Z_{New} (m, l) \] (18)

where,
\[ Z = V_m - \sum_{k=1}^{N_p} Z_{New} (i, k) \times I_k \] (19)

Eq.(16)-(18) are solved to get the required phasors to get the DF value from eq. (15). If the number of equations is less than required to solve the unknown phasors in an area (due to lower number of buses in an area), the area is modified considering the PMU information from the nearest interconnected PMU buses to form the new boundary buses, such that the buses inside the modified area forms a closed loop. For a data loss at a PMU bus in an area, if a fault occurs in other areas, the faulted area can still be determined using CAC. The scheme then determines the faulted line using DF calculation in the faulted area. However, if none of the CAC is able to determine the faulted area, the scheme proceeds to perform FLI for the area consisting of PMU with data loss. Flowchart of the proposed scheme is shown in Fig. 2.

III. PERFORMANCE ASSESSMENT AND DISCUSSION

The proposed scheme is implemented on a New-England 39-bus system using MATLAB/Simulink platform as shown in Fig.3. The power system is divided into six coherent areas [20]. For finding the FDI, the phasor information at the generator buses and boundary buses separating connected areas are utilized. IEEE C37.118.1 compliant P-class PMUs [27] with a reporting rate of 60 frames/ second for fetching the phasor data are utilized. The PMUs are placed at fifteen buses according to the placement rules described in Section-II (A) and are marked in red color as shown in Fig.3. FDI is calculated considering all data available and PMU data loss. A fixed threshold ‘\( \phi \)’ is selected as ‘−0.0001’ by considering FDI for fault cases far-away from all the generator buses in all areas. The adaptive threshold ‘\( k \)’ for FDI...
TABLE 1. Area division for CAC and DF calculation in 39-bus system.

| Area | Protected lines | PMU Buses | DF with data loss |
|------|----------------|-----------|------------------|
| 1    | 39-1,2-1,39-9,8-9 | 39,2,8    | No               |
| 2    | 4-5,4-14,8-5,8-7,6-7,6-11,10-11,10-13,13-14,14-15,15-16 | 4,6,8,10,16 | Yes              |
| 3    | 16-19           | 16,19     | No               |
| 4    | 22-21,22-23,23-24,16-24,16-21,16-17,16-19 | 22,23,16,17,19 | Yes              |
| 5    | 26-28,28-29,26-29 | 26,28,29  | No               |
| 6    | 17-27,27-26,25-26,25-2,2-3,3-4,3-18,17-18 | 2,25,26,4,17 | Yes              |
| 7    | 39,9,8,9,7,8,5,8,4-5,6-7,1,2,1,39 | 2,39,4,6,8    | Yes              |
| 8    | 17-27,27-26,25-26,26-28,28-29,26-29 | 25,17,26,28,29 | Yes              |

The index are calculated with and without PMUs. Whenever, a device failure or data loss is detected from a PMU bus, the measurement from those PMU buses are discarded and the index calculated with PMU loss is taken into account.

A. STABLE POWER SWING CONDITION

Stable power swing condition are power system oscillations caused as a result of switching operations, generator disconnection, switching on or off of large loads etc., [28]. To access the performance of the proposed scheme for stable power swing, a fault at line 29-26 is created at 0.3 s and subsequently isolated by opening the line end circuit breakers at 0.4s. Fig. 4(a) shows the index values derived from the connected areas with all data available and are well above the threshold values verifying a no fault situation. Fig. 4(b) shows the indices derived for connected areas when the PMU data are absent at different buses. The PMUs which are absent are shown inside the ‘()’ in Fig.4 (b). For example, for loss of information at bus-28, PMU placed at bus-26 is used to derive FDI between area-5 and 6. Similarly, eq. (5) and (6) are used to derive the indices for loss of information at any of the generator buses.

B. LOAD ENCROACHMENT CONDITION

An increase in load at some of the buses may cause a reduction in apparent impedance at a bus, thus resulting in third zone relay malfunction. Performance of the proposed scheme for load encroachment condition is analyzed by increasing load at bus-8 to an amount that meets the criteria for loadability limit assigned by North American Electric Reliability Council (NERC) [3]. An increase in load at bus-8 causes a deviation in FDI. However, all the indices are positive deducing a no fault situation for all the required data available as well for PMU failure at some of the buses as shown in Fig. 5(a) and 5(b).

C. VOLTAGE STRESSED CONDITIONS

The reactive loads at buses 3, 17 and 27 are increased simultaneously to assess the performance of the proposed scheme for voltage stressed conditions. The FDI for all the areas are illustrated in Fig. 6(a) for all the data available and Fig. 6(b) for PMU loss at some buses. It is observed that the indices are...
shrinkage and well above the threshold of $-0.0001$, hence no fault is detected.

D. SYMMETRICAL FAULT CONDITION

A solid three-phase fault is created at line 3-18 at 1s. Fig. 7 illustrates that the FDI index shows negative deviation below the threshold, following the fault. Hence, fault is detected after it stays there for 3 samples. After, the condition for fault is satisfied, the faulted area is identified using the method described in section II.B. The CAC for area-6 shows a positive deviation above the threshold value. For performing the task of FLI, the lines within the faulted area are considered. The fault distance to fault ($DF$) for line 3-18 is found to be ‘0.5001’ and the other lines is beyond the range of 0 to 1, irrespective of data loss from any of the PMU buses in area-6.

E. HIGH RESISTANCE FAULTS

The sensitivity of the line protection towards high resistance faults is vital for ensuring the dependability of a scheme. Line to ground fault (L-G fault) with fault resistance of 200 $\Omega$ is initiated at line 39-9. It is observed that the FDI indices for this case crosses the threshold after the fault inception. Moreover, the CAC index shows a positive deviation in area-1. Hence, the faulted line is identified within faulted area as 39-9 with $DF$ as ‘0.4979’. For data loss in any of the PMU buses in area-1, the available voltage phasors are from two PMU buses. To find the $DF$, the area-1 is modified to include PMU buses 4 and 6 to form a closed loop with modified area-7 from Table-1.

F. IMPACT OF PMU MEASUREMENT ERROR

In order study the effect of PMU errors on the proposed scheme, Gaussian noise with Signal to Noise ratio (SNR) of 20 dB are added to the magnitudes and angles of all the PMU measurements. The FDI with their thresholds (indicated by dashed lines) for pre- fault case is shown in Fig. 9(a), verifies a no fault, since the index does not cross their threshold for three consecutive cycles. For observing the proposed scheme during fault scenarios, two different types of fault are studied. Line-line-line (LLL) fault of 5 $\Omega$ and L-G fault of 200 $\Omega$ is created at line 16-24 at 90% and 10%, respectively from bus-16. It is observed from Fig. 9(b) that for symmetrical fault the FDI crosses their thresholds for three consecutive cycles, detecting a fault situation. The CAC is taken into account after the fault is detected and, area-4 is detected as a faulted area as observed from Fig 9(c). The FLI is carried out for the lines inside area-4. The faulted distance from calculated voltage and currents corresponding to line 16-24 is found to be “0.9053”, irrespective of the data loss at any of the PMU buses in this area. The closest value of DF in this case is for line 23-24 of “1.0192” which is outside the 0-1 range.

Similarly, for unsymmetrical fault, the FDI and CAC are shown in Fig. 10(a) and 10(b). The fault location is found to be “0.206” which is not the exact location of the fault. However, it still determines the faulted line as 16-24, since, all the other lines have the values beyond the range of 0 to1 with line 23-24 as the closest value of ‘1.144’. Hence, the proposed scheme identifies the faulted line irrespective of the inaccuracies pertaining to PMU errors.
for three consecutive sample duration. The average fault detection time for the proposed scheme with reporting rate of 60 frames/sec neglecting the PMU latencies and including the wait time of 3 samples for fault detection is approximately 60 ms. The inclusion of latencies associated with PMUs i.e., data processing, transducer delays and communication medium (of maximum 200 ms) accounts for response time of approximately 260 ms [29], [30], which is well within the time required for third zone operation (1000-1800ms) for back-up relaying. Table 2 illustrates the index values for fault on different lines with different fault types, fault resistances ($R_f$) and fault distance (D %). From Table 2, we observe that the FDI magnitudes for symmetrical fault cases are lower than that for unsymmetrical fault cases. This is because, for symmetrical fault cases, FDI amounts to PCPA. Hence, it is detected using the fixed threshold of $\ll -0.0001 \gg$. However, for unsymmetrical fault cases, the PCPA magnitudes are usually lower than the magnitudes of summation of negative and positive sequence currents in an area. The current summation is also dependent on the severity of fault i.e., fault type, fault resistance and fault location. Hence, the FDI for unsymmetrical faults have usually higher magnitudes than that of symmetrical faults and are detected using adaptive threshold. For each faulted line, the CAC with the affected area in bracket is given. The DF for the faulted line is given which lies between the range of 0-1. The DFs for other lines closest to this range is also given with the respective line in the bracket. This shows that the proposed scheme is dependable as well as secure to find the correct fault location.

IV. COMPARATIVE ASSESSMENT

As discussed in section-I, paper [19] has dealt with the dependability for PMU unavailability at critical buses. It assumed an initial PMU placement at both the ends of the lines. This is not advisable due to economic constraints. With the unavailability at any one of the buses, the data from the interconnected buses are utilized.

Suppose, a symmetrical fault occurs at line 3-18 and data at bus-18 is not available. The voltage at bus-3 is calculated from 2, 4 and 17. However, the faulted line cannot be found with unavailable data at bus-18. Hence, for the buses connected to only two adjacent buses, the PMU data is required at all the three buses to find the faulted line. Moreover, the scheme always requires the PMU availability at least one.
of the terminal of all the lines for faulted line identification. However, in the proposed scheme, the PMU is initially placed at fewer buses. Moreover, the faulted line can be identified even if two adjacent buses do not have PMU installed on them provided the presence of PMU information at the generator buses in the faulted area as shown in section III.D, where fault at line 3-18 is detected even if there is no PMU at buses 3 and 18. The comparative assessment of the proposed scheme with few existing schemes with respect to different parameters is shown in Table 3. Comparative assessment with some existing schemes suggests following benefits of the proposed scheme over these schemes:

1) Lesser PMU requirements leads to lesser device and infrastructure cost making the back-up protection scheme economical.

2) The proposed schemes are dependable as well as secure for different stressed conditions even if PMU data at some of the buses becomes unavailable.

3) The proposed scheme is found to be reliable even during the presence of PMU measurement errors.

4) The task of faulted area identification and FLI is carried out only when fault is detected. This reduces PDC congestion. Moreover, determination of faulted area before FLI also reduces the end-to-end latencies at faulted line identification stage.
TABLE 3. Performance comparison of proposed scheme with existing schemes.

| Papers | PMU requirement | Data loss | PMU error | Stressed condition |
|--------|-----------------|-----------|-----------|--------------------|
| Proposed | Low | Yes | Yes | Yes |
| [6] | High | No | No | No |
| [7]-[13] | High | No | No | Yes |
| [14] | Low | No | No | Yes |
| [15] | Low | No | Yes | Yes |
| [16] | High | No | No | No |
| [17] | Low | No | Yes | No |
| [18] | Low | No | Yes | No |
| [19] | Low | Yes | No | Yes |

V. CONCLUSION

The proposed scheme enhances the reliability of the wide-area back-up protection scheme for PMU data unavailability which may arise due to PMU device malfunction or communication failure. The scheme comprises of three steps, i.e., fault detection, faulted area identification and faulted line identification. At each step, the index derivation with unavailability of PMU data at system buses is considered. The faulted line is determined using the bus-impedance matrix, reducing the computational burden. The performance assessment for the proposed scheme is carried out on a New-England 39-bus system with fewer PMU placement for various faults as well as stressed conditions including the cases with non-availability of PMU data at some of the PMU buses. The proposed scheme is also tested with measurement error of 20 dB SNR from PMUs. It is observed from the performance results of the extensive test cases and the comparative assessment with existing schemes that the scheme is highly capable of providing backup protection measure during PMU data loss. The maximum response time of is 260 milliseconds including the PMU latencies which is well within the delay associated with third zone operation of distance relays.

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