IET Generation, Transmission & Distribution

Research Article

Online detection of tripped transmission line to improve wide-area SA in power transmission system

ISSN 1751-8687
Received on 4th December 2016
Revised 7th July 2017
Accepted on 27th August 2017
E-First on 18th October 2017
doi: 10.1049/iet-gtd.2016.1964
www.ietdl.org

Manas Kumar Jena[1] ✉, Bijaya Ketan Panigrahi[1], Subhransu Ranjan Samantaray[2]

[1]*Electrical Engineering Department, Indian Institute of Technology, Delhi, India*

[2]*School of Electrical Sciences, Indian Institute of Technology, Bhubaneswar, India*

✉ *E-mail: kumarmanas87@yahoo.com*

Abstract: This study presents a new methodology for fault-induced line outage detection in the power transmission network. Pre-fault operating conditions and synchronised phasor measurements at all generator buses are used to accomplish this task. Initially, the proposed scheme divides the whole power system under study into different protection zones corresponding to generator bus (es). Furthermore, a new index termed as 'gain in momentum' (GIM) at each generator bus is used to identify the expected tripped region (ETR). This information helps in reducing the search space. Once the ETR is identified, online measured power flow of line connected to generator of ETR having maximum GIM is compared with the estimated post-outage power flow of the same line. The post-outage power flow is obtained using pre-outage line flow and line outage distribution factor. The aforementioned power flow comparison helps in identifying the tripped transmission line. The performance of the proposed scheme is validated on the IEEE-39 bus New England system and 246-bus North India Grid using the Power System Simulation for Engineering software. The test results indicate that the proposed scheme is highly effective in identifying the tripped line of a transmission system.

1 Introduction

Improving situational awareness (SA) using phasor measurement unit (PMU) information is one of the most challenging task in today's modern power system. It is also reported that most of the recent blackouts including four major North American blackouts and the 2012 northern India blackout were due to lack of SA [1–4]. One of the major aspects of SA is online detection of line outage. Online line outage detection will not only help in predicting post-fault dynamic behaviour of the power system but also to track cascaded line outages. PMUs are now deployed in most part of the Indian power grid and the information from these PMUs can be used efficiently to observe dynamic behaviour of the system following any contingency. Thus, new methodologies to enhance wide-area SA in power system are mandated.

Various schemes are suggested regarding correct topology detection following any contingency. Most of these methods rely on SCADA information and breaker status which is a time-consuming process. In recent times, PMU informations are used in applications such as WA protection, state estimation (SE), dynamic security assessment [5–10] etc. PMUs are also used to identify the tripped transmission lines [11–21]. Voltage phasor angle measurement-based single line and double line outage detection techniques are reported in [11, 12], respectively. A support vector machine-based techniques are suggested in [13]. The Markov dependency graph model is reported in [14], where it is assumed that the PMUs cover the entire system. A sparse overcomplete representation-based line outages detection technique was proposed in [15]. Techniques such as cross-entropy-based optimisation and ambiguity group theory were presented in [16, 17], respectively. In [18], statistical properties of voltage phase-angle measurements are used to identify the line outage. Hidden Markov models are also used to accomplish the task of dynamic detection of transmission line outages [19]. Li *et al.* of [20] have investigated the impact of PMU with bad data on the line outage detection technique. Recently, a normalised kinetic energy-based scheme is reported in [21]. Most of the recently proposed schemes require higher number of PMUs to be installed in the existing power system. However, if the same objective can be fulfilled with minimal number of PMUs, then the scheme will be considered economical. In a power system, the numbers of generator buses are quite less as compared with total numbers of buses. Thus, installing PMUs only on the generator buses is an economically viable option.

In the proposed scheme, the power system under study is divided into different protection zones (PZs) corresponding to one or more generator bus (es). The gain in momentum (GIM) of all generators during the first 0.1 s of a transmission line fault is monitored. In real time, following a transmission line fault, the GIM information of all the generators are used to locate the expected tripped region (ETR). Then, online measured power flows of line(s) connected to generators of ETR are compared with the estimated post-outage power flows of the same lines. The post-outage power flow is estimated using pre-outage line flow and line outage distribution factor (LODF) [8, 22].The aforementioned power flow comparison helps in identifying the tripped transmission line.

The remainder of this paper is organised as follows: the detailed methodology of the proposed scheme is presented in Section 2. The simulation results of using the proposed scheme over IEEE-39 bus system and the practical 246-bus northern regional power grid (NRPG) of India are provided in Section 3. A small discussion section is presented in Section 4. Finally, the conclusions of the research work are provided in Section 5.

2 Proposed methodology

The dynamics of the generator following a fault can be governed by (1) [23]:

$$M\frac{d^2\delta}{dt^2} = P_m - P_e = P_a \quad (1)$$

where M is the inertia constant, δ is the rotor angle, P_m and P_e are the mechanical and electrical powers, respectively, and P_a is the accelerating power. During dynamic behaviour, the speed of the generator can be calculated in terms of the change in rotor angle as follows:

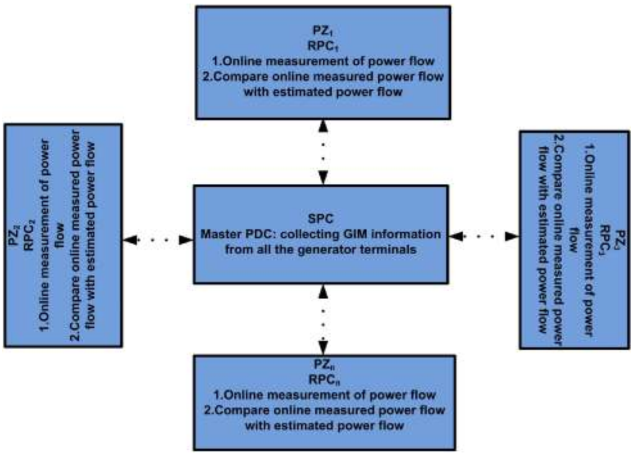

Fig. 1 *Architecture of the proposed scheme*

$$\omega = \frac{d\delta}{dt} \tag{2}$$

The rotor angle cannot be directly measured by PMU. Furthermore, rotor angle calculation needs numerical method which is very time consuming. Therefore, rotor angle estimation is required. Having estimated the rotor angle of the generator using terminal variables measured by PMU, at consecutive interval times $t(i)$, $t(i+1)$ and $t(i+2)$, generator rotor speed can be calculated by (3), (4) [23]

$$\omega(i) = \omega_0 + \frac{\delta(i+1) - \delta(i)}{t(i+1) - t(i)} \tag{3}$$

$$\omega(i+1) = \omega_0 + \frac{\delta(i+2) - \delta(i+1)}{t(i+2) - t(i+1)} \tag{4}$$

2.1 Identification of ETR

GIM is defined as

$$\text{GIM}_n = M_n \times (\Delta\omega)_n \tag{5}$$

where GIM_n is the GIM of each machine 'n' and M_n is the moment of inertia of each machine 'n'

$$(\Delta\omega)_n = \omega(i+1) - \omega(i) \tag{6}$$

$(\Delta\omega)n$ is the gain in speed of each machine in first 0.1 s following fault. In the proposed scheme, GIM is chosen as an indicator of ETR because of the following reasons. Real power output from a synchronous generator reduces when the fault MVA fed by the generator increases. Thus, the GIM of the generators in first 0.1 s of a fault is proportional to the fault MVA supplied by the generator. The GIM of a generator during the first 0.1 s is almost zero if the generator is located far away from the fault point. Therefore, the GIM of a generator is much higher and sensitive to the fault location when the fault is on nearby lines. Thus, GIM of a generator will be an effective indicator for ETR.

In the proposed scheme, the power system is divided into several PZs as shown in Fig. 1. This is done in order to minimise the search space. This information will also help in identifying the area in which some disturbance such as fault followed by line tripping has occurred. Each PZ is having its own regional protection centre (RPC). There can be one SPC which collects GIM information of all the generators. In practical Indian system, we have state load dispatch centres (SLDCs) operating at the state level. Furthermore, there is regional LDCs (RLDCs) at each region and national LDCs at the national level. SPC can be operated at RLDC which consists of many SLDCs. Each SLDC can be operated as an RPC. There must be a reliable and dedicated communication medium between the SPC and RPC. Table 1 shows the PMU location of each test system considered for the proposed scheme. An offline analysis was made for each test system in order to divide the whole system into several PZs. Initially, the original system is divided into different PZs looking at the location of generators in the system. For example, in IEEE-39 bus system, G6 and G7 are electrically close to each other, and thus they are placed in one zone. Accordingly, the IEEE-39 bus system is divided into eight PZs.

Table 1 Buses belonging to each PZ of different test systems

Test system	Numbers of PMU used	Buses having PMU
IEEE-39 bus system	10	30, 31, 32, 33, 34, 35, 36, 37, 38, 39
reduced 246-bus North India Grid	58[a]	all generator buses

[a]Total 60 generators are there in the system. Two generators are out of service.

The next task is to allocate the number of buses to be included in each PZ. To accomplish this task, different types of transmission line faults (line-to-ground, line-to-line, line-to-line-to-ground and three phase) are simulated in each PZs. Fault impedance is varied from 0.01 to 100 Ω. Fault location is varied from 10 to 90% of line length at a step size of 10%. Positive sequence voltage magnitudes (PSVMs) of all the buses along with GIM of all generators during the first 0.1 s of a fault on all the lines one at a time are monitored. Both the GIMs of all the generators and PSVMs of all the buses of the system are used as input to a decision tree (DT) [24]. The output of the DT was set to 0 – for no fault situation and 1 – for faulted situation. DT algorithm has two important attributes termed as 'variable importance' and 'correlation' which help in identifying most valuable input variables. 'Variable importance' help in weighing the input variables in terms of their contribution in predicting the target output/class. 'Correlation' helps in eliminating redundant input features [24]. Thus, looking at the trained DT, the generators whose GIM values are taking part in final decision making for detecting fault in PZ1 are included in PZ1. Similarly, the buses whose PSVMs are taking part in final decision making in detecting fault in PZ1 are included in PZ1. Similarly, generators and buses are allocated to each PZ of each test system as summarised in Table 2. The task of building DT in order to get different PZs of each test system is accomplished using open source R-software package [24]. The DT which is used to divide the power system under study into different VPZs is trained with the following three conditions:

- Fault with all the lines and generators intact.
- Fault with (N−1) contingency.
- Fault with (N−2) contingency.

Here, the primary objective is fast identification of ETR using GIM information at the SPC. In real time, PMUs provide GIM information to the SPC where all the GIM values are arranged in the descending order. Following a fault in the transmission line, the generator with maximum GIM indicates the ETR. Once the ETR is identified, then the RPC of the corresponding PZ will identify the tripped line comparing the power flow information of each line connected to the generator.

2.2 Power flow estimation using LODF

On the basis of DC power flow, the change in voltage angle according to the change in active power is expressed as [22]

$$\Delta\theta = [X]\Delta P \tag{7}$$

LODF is used to estimate the change in power flow in a line following a tripping of another line [22]. As shown in Fig. 2, line l is surrounded by buses i, j and line k is surrounded by buses m, n. It is desired to observe the effect of tripping of line k on line l. Thus, the LODF is defined as [22]

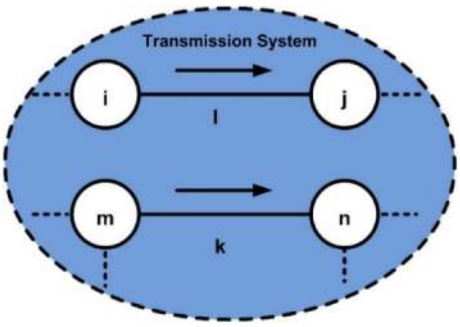

Fig. 2 *Sample transmission system used to define LODF*

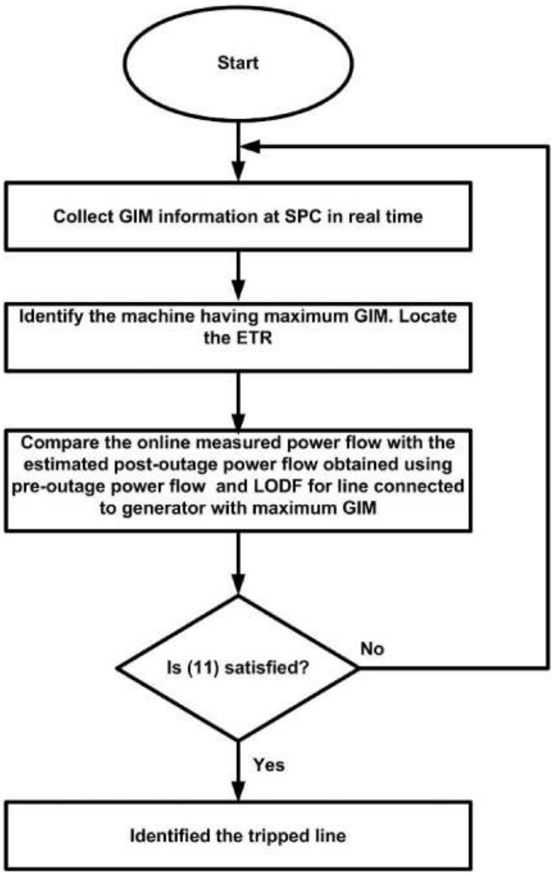

Fig. 3 *Flowchart of the proposed scheme*

$$d_{l,k} = \frac{\Delta P_l}{P_k^0} \quad (8)$$

where $d_{l,k}$ is LODF; ΔP_l is the change in power flow in line l; and $P_k{}^0$ is the base case flow on line k.

LODF can be calculated by using (5) [22]

$$d_{l,k} = \frac{\frac{x_k}{x_l}(\boldsymbol{X}_{in} - \boldsymbol{X}_{jn} - \boldsymbol{X}_{im} + \boldsymbol{X}_{jm})}{x_k - (\boldsymbol{X}_{nn} + \boldsymbol{X}_{mm} - 2\boldsymbol{X}_{nm})} \quad (9)$$

where x_k is the reactance of the kth line; x_l is the reactance of the lth line; *and* X_{nm} is the m, nth element of $\boldsymbol{X}$ matrix of (3).

Equation (9) shows that LODF can be calculated using the elements of $\boldsymbol{Z}$-bus matrix along with the line data. Hence, the calculation of LODF can be made at the SPC and the results can be sent to the RPC, so that the post-outage power flow can be estimated. Following an outage of line k, the power flow on line l can be estimated by:

$$\widehat{P_l} = P_l + d_{l,k}P_k \quad (10)$$

Table 2 Buses belonging to each PZ of different test systems

Test system	Number of PZs	Buses belonging to Each PZ
IEEE-39 bus system	8	$PZ_1(G_1)$ – 1, 2, 9, 8$PZ_2(G_2)$ – 5, 6, 7$PZ_3(G_3)$ – 10, 11, 13, 14$PZ_4(G_4)$ – 15, 16, 19$PZ_5(G_5)$ – 16, 19, 20$PZ_6(G_6, G_7)$ – 21, 22, 23, 24$PZ_7(G_8, G_9)$ – 25, 26, 27, 28, 29$PZ_8(G_{10})$ – 1, 3, 4, 17, 18
reduced 246-bus North India Grid	46	[a]

[a]Owing to space limitations buses belonging to each PZ of reduced 246-bus North India Grid is not mentioned here.

where $\widehat{P_l}$ is the power flow of line l following line outage; P_l is the power flow of line l before line outage; and P_k is the power flow of line k.

Once the ETR is identified, the tripped line can be recognised comparing the measured and estimated power flows of the line connected to the generator bus with maximum GIM. The online measured post-outage power flow is compared with the estimated post-outage power flow. The estimated power flow can be obtained from pre-outage power flow and LODF. If the difference between the measured power flow and estimated power flow is within a tolerance (ε) with respect to a particular line outage, then the corresponding line is identified as the tripped transmission line. The reason behind keeping a tolerance is to accommodate some errors which are inherent while measuring the line flows. Furthermore, the estimation is based on DC power flow which involves few assumptions to simplify the load flow problem. Thus, the line outage identification criteria can be written as follows:

$$\left|P_l^m - \widehat{P_l}\right| < \varepsilon \quad (11)$$

where $\widehat{P_l}$ is the estimated post-outage line flow; P_l^m is the measured post-outage power flow; and ε is the tolerance.

In this paper, the tolerance is kept at 10%. This includes 1% CT error, 1% PT error, 3% device errors and 5% calculation errors.

Fig. 3 shows the flowchart of the suggested scheme. The PMUs are installed at the generator buses of the power system and constantly monitoring the GIM of each generator in real time. The fault clearance normally takes 5–6 cycles. Thus, the generators which are located nearer to the fault location will have a large GIM. This information will help in minimising the search space. As shown in Fig. 3, the GIM informations obtained from the PMUs installed at the generator terminal are used to locate the ETR. Once the ETR is identified, the corresponding RPC will monitor the power flow information of line connected to the generator having maximum GIM. The power flow through the same transmission line is further estimated using **LODF** matrix. The assumed tripped line for which the error between the measured and estimated power flow is minimum is identified as the tripped transmission line. In the proposed paper, it is assumed that pre-fault power flow is estimated at the RPC using SCADA data. The base case topology can be found using newest SE algorithm. One of the advantages of the proposed scheme is that the power flow measurement information of only the line connected to the generator with maximum GIM is required. Thus, for that selected line power flow will be estimated using the **LODF** matrix. This greatly reduces the computational burden of the tripped line identification scheme.

3 Test cases and result analysis

The proposed online line outage detection scheme is validated on two different test systems using Siemen's commercial simulation software package named Power System Simulation for Engineering (PSS/E). The test systems are as follows:

- IEEE-39 bus system.

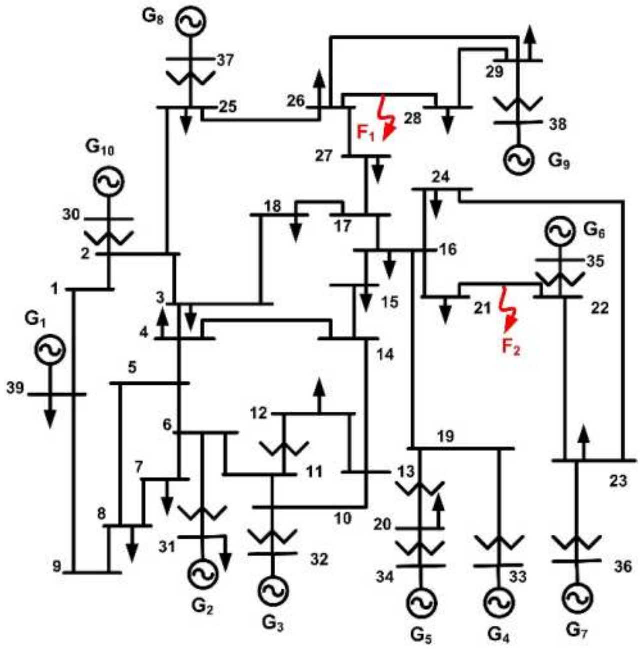

Fig. 4 *Single line diagram of IEEE-39 bus system*

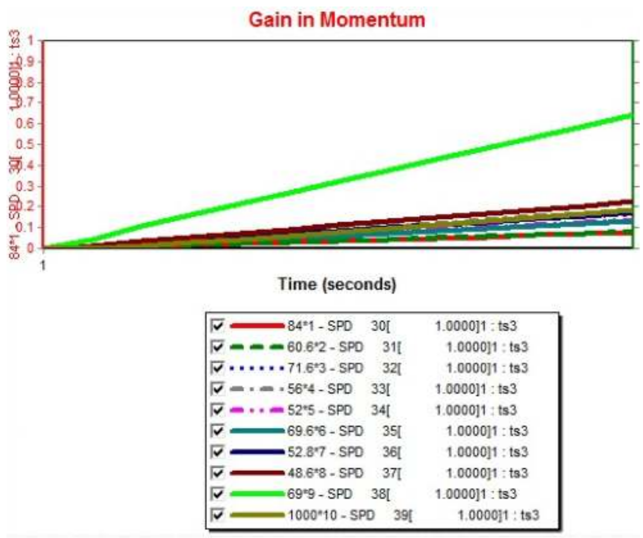

Fig. 5 *GIM of the generators following a fault on line 26–28 of IEEE-39 bus system*

- Indian 246-bus system (reduced North India Grid).

3.1 IEEE-39 bus system

The single line diagram of IEEE-39 bus system considered for the validation of the proposed scheme is shown in Fig. 4. The system data required for simulation in PSS/E environment are obtained from [25]. Table 3 shows some portion of **LODF** matrix obtained using the line data of the test system. **LODF** matrix is stored in such a way that each row and column corresponds to one line in the power network. The row corresponds to the line under monitoring and the column corresponds to the tripped line. As the IEEE-39 bus system constitutes 46 numbers of transmission lines, thus the size of the **LODF** matrix is 46 × 46. The results are discussed below:

- *Balanced fault on line 26–28:* A three-phase fault was simulated on line 26–28 at 1 s. As shown in Fig. 5, GIM of G9 (bus-38) is increasing sharply following fault inception. The GIM for G9 indicate that the fault is inside PZ7 (Table 2). Thus, PZ7 is identified as the ETR. Once the ETR is identified, the online measured line flow is compared with the estimated line flow. The power flow estimation was carried out using the **LODF** matrix (Table 3) of IEEE-39 bus system. As the line outage is under PZ7, thus the MW flow of line connected to G9 of PZ7 is monitored (line 29–38). The power flow in line L_{45} is estimated using the **LODF** matrix and the base case flow. The estimation was carried out assuming lines such as L_4, L_{30}, L_{31}, L_{32}, L_{33} and L_{34} as tripped lines. The percentage error between the estimated flows and the flow obtained through PSS/E simulation is depicted in Table 4. It is observed that the error between the estimated power flow and the measured power flow corresponding to the line L_{32} (line 26–28) is minimum. The difference fulfils the criteria (11). Thus, L_{32} (line 26–28) is identified as the tripped transmission line.

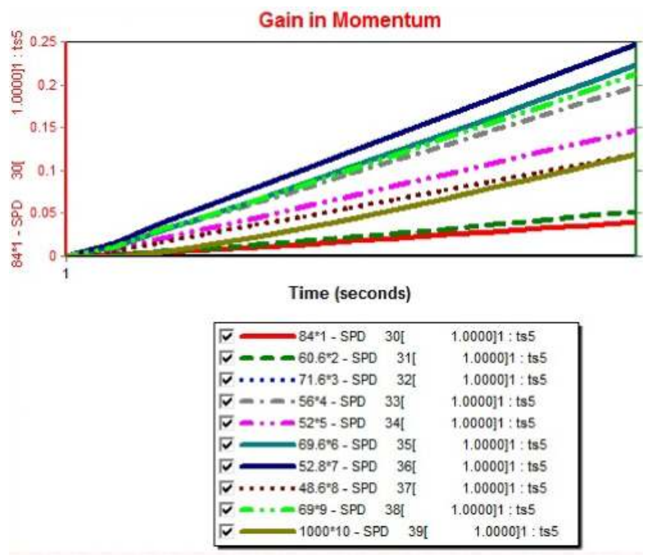

Fig. 6 *GIM of the generators following a fault on line 21–22 of IEEE-39 bus system*

- *Unbalanced fault on line 21–22:* Total fault MVA supplied by all the generators varies for different types of faults. When fault MVA supplied by the generator increases, real power transfer from a generator decreases (i.e. accelerating power increases) [33, Ch. 6]. Therefore, the GIM by the generators in first 0.1 s of a fault is proportional to the fault MVA supplied by the generator. To check the performance of the proposed scheme during unbalanced fault condition, a high-impedance line-to-ground was simulated on line 21–22 at 1 s. The GIM of all the generators following the unbalanced fault on line 21–22 is monitored at the SPC and all the GIM values are arranged in the descending order. The generator with maximum GIM indicates the ETR. As shown in Fig. 6, GIM of G7 (bus-36) is increasing sharply following the fault inception. The GIM for G7 is maximum which indicates that the fault is inside PZ6 (Table 2). Thus, PZ6 is identified as the ETR. Once the ETR is identified, the online measured line flows of line L_{42} (line 23–36) is compared with the estimated line flow. The power flow in line L_{42} is estimated using the **LODF** matrix and the base case flow. The estimation was carried out assuming lines such as L_{23}, L_{27}, L_{28} and L_{29} are the tripped lines. The percentage error between the estimated flows and the flow obtained through PSS/E simulation is depicted in Table 5. It is observed that the error between the estimated power flow and the measured power flow corresponding to the line L_{27} (line 21–22) is minimum. The difference fulfils the criteria (11). Thus, L_{27} is identified as the tripped transmission line.

3.2 Reduced North Regional Power Grid (India)

NRPG of Power Grid Corporation of India Limited is the largest among all five regional power grids in India [27]. The reduced NRPG (220 and 400 kV only) network only consists of 246 buses, 376 branches (lines/transformers) and 40 shunt reactors. The detailed line data, bus data and the dynamic data required for the

Table 3 Part of **LODF** matrix for IEEE-39 bus system

	L_1	L_2	L_3	L_{46}
L_1	0	1	−0.35456	0.167
L_2	1	0	0.354556	0
L_3	−0.80088	0.8008	0	−0.456
⋮	0	0	0	0
L_{46}^{***}				

Table 4 Error comparison of measured and estimated power flows

Assumed tripped line	%Error
L_4	32.32
L_{30}	32.30
L_{31}	35.16
L_{32}	**2.32**
L_{33}	28.16
L_{34}	28.92

Bold values indicate tripped line

Table 5 Error comparison of measured and estimated power flows

Assumed tripped line	%Error
L_{23}	28.32
L_{27}	**3.14**
L_{28}	33.35
L_{29}	28.14

Bold values indicate tripped line

dynamic modelling of the NRPG system using PSS/E software are available at [28]. As the NRPG-246-bus system constitutes 376 numbers of transmission lines, thus the size of the **LODF** matrix is 376 × 376. The simulation results for some of the test cases are discussed below:

1) *Fault on line 62–71:* A symmetrical fault was initiated on line 62(WAGORA4)-71(KISPUR4) at 1 s. In this test system, G3 and G4 are kept in PZ2 which includes 11 buses in its zone (3, 4, 49, 51, 52, 54, 56, 62, 71, 72, 73). Fig. 7 shows that GIM of G4 is maximum following the fault inception which indicates that the fault is inside PZ2. Thus, PZ2 is identified as the ETR. Once the ETR is identified, the online measured line flows of line L65 which is directly connected to G4 is compared with the estimated line flow. The power flow in line L65 is estimated using the **LODF** matrix and the base case flow. Table 6 shows the some portion of **LODF** matrix obtained using the line data of the test system. The estimation was done assuming lines corresponding to PZ2 are the tripped lines. The percentage error between the estimated flows and the flow obtained through PSS/E simulation is given in Table 7. It is observed that the error between the estimated power flow and the measured power flow corresponding to the line L67 is minimum. The difference fulfils the criteria (11). Thus, L67 is identified as the tripped transmission line.

To test the dependability of the proposed scheme for different types of faults, all ten types of shunt faults are simulated on the NRPG-246-bus system. The results corresponding to some of the test cases are summarised in Table 8. It is observed that the proposed scheme is able to identify the tripped transmission line with high efficacy irrespective of variations in fault type, fault resistance and fault location.

2) *Effect of PMU error:* IEEE Standard C37.118–2011 details the general total vector error requirement for PMU measurements [26]. The effect of PMU uncertainty varies from application to application. In this paper, we tested the effect of PMU error on the detection accuracy of the proposed scheme. Magnitude error of <1% and phase-angle error of <0.573° is considered in this paper

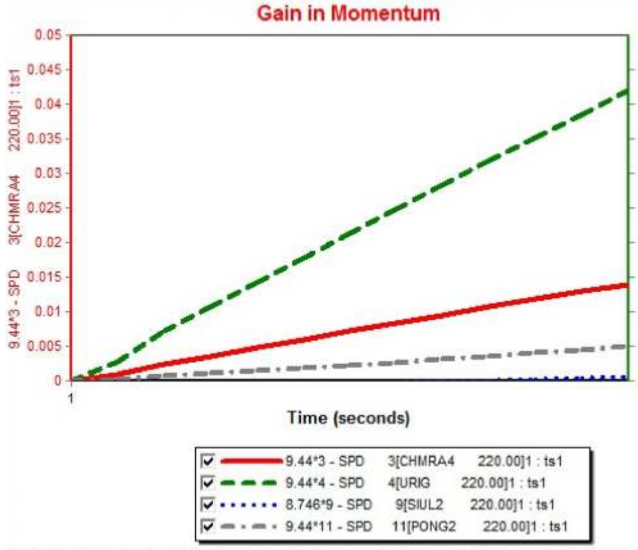

Fig. 7 *GIM of the generators following a fault on line 62–71 of NRPG*

Table 6 Part of **LODF** matrix for NRPG-246-bus system

	L_1	L_2	L_3	L_{376}
L_1	0	0	−0.00159	0
L_2	0	0	0	0
L_3	0.001522	0	0	0
⋮	0.013558	0	0.827468	0
L_{376}	0	0	0	0

[26]. In the NRPG-246-bus system, from each PZ, two line outage cases are tested. Thus, in total 92 test cases are repeated with variations in PMU measurement error. The result is depicted in Table 9. It is observed that increase in phase-angle error is mostly affecting the proposed scheme. This is because of the sensitivity of GIM to phase-angle measurement of PMU. However, this is an empirical result. A detailed analysis is required in order to come up with a generalised conclusion regarding the effect of PMU error on the tripped line identification scheme. Similar work regarding an extensive analysis of effect of PMU uncertainty on line outage detection is reported in [26].

4 Discussion

The previous sections discuss the proposed online tripped line identification scheme and simulation results on two test systems are presented. Furthermore, the analytical finding of the proposed research work is presented as follows.

4.1 Impact of fault duration on GIM

1. Fault duration will affect the generator angles which directly affects the accelerating power output from the generator.
2. Furthermore, the output power of a generator is fed either to the loads directly connected to the generators or power fed to the other load/generator buses. The power fed to the other load/generator buses depend on the angular difference between the generators.
3. If the generators are close to the fault location, then the reduction in power output and thus the accelerating power is very high. The reduction is mainly due to increase in shunt susceptance. Thus, in this case the power fed to the fault is independent of angles between the generators [29].
4. The other type of power which is fed to the load/generator bus is sensitive to angle difference between the generators. Furthermore, in case of generators which are electrically close, the change in output power is mainly decided by the change in angle difference. This happens because in case of generators

Table 7 Error comparison of measured and estimated power flows

Assumed tripped line	%Error
L_4	30.12
L_{39}	35.11
L_{42}	28.14
L_{43}	31.33
L_{49}	32.18
L_{50}	29.13
L_{52}	36.33
L_{53}	34.13
L_{54}	29.88
L_{55}	36.11
L_{56}	26.42
L_{57}	28.11
L_{63}	33.14
L_{64}	30.16
L_{65}	29.53
L_{67}	**5.15**
L_{96}	25.11
L_{99}	33.66
L_{100}	32.15

Bold values indicate tripped line

Table 8 Performance of the proposed scheme for different types of faults

Faulted line	Fault type	Fault distance, %	Fault resistance, Ω	Identified line
40–211	AG	12	1	40–211
239–241	AB	55	1	239–241
244–245	ABG	75	1	244–245
21–37	ABC	88	1	21–37
150–34	AG	8	100	150–34
118–232	AB	55	100	118–232
106–107	ABG	70	100	106–107
13–90	ABC	90	100	13–90

Table 9 Effect of error in PMU measurement on the proposed scheme

Error type	False identification (out of 92 cases)
no error	0
0.5% (magnitude)	0
1% (magnitude)	2
0.2^0 (phase angle)	3
0.573^0 (phase angle)	5

which are located close to each other, equivalent admittance between them is high as compared with the generators which are having high electrical distance between them.

5. The generators which are electrically close accelerate together during the fault. Thus, change in fault duration will have minimal impact on angle difference between these generators which are electrically close. The impact will be more for generators which are electrically far apart.
6. Therefore, in case of generators which are close to each other, the angle difference between them is more or less insensitive to changes in fault duration. Thus, the accelerating power remains almost constant with change in fault duration which indirectly tells that the GIM is also insensitive to changes in fault duration.

Table 10 Comparative analysis

	[17]	[21]	[27]	Proposed scheme
PMU coverage	all buses	only generator bus	more than the proposed scheme	only generator bus
requirement of power flow measurement	–	lines connected to all the generator bus	–	only line connected to the generator with maximum GIM
consideration of fault-induced outages	no	yes	no	yes
dependency on large training data	no	yes	no	no
time of operation	0.2–0.8 s	around 0.2 s	around 5–6 s	<0.2 s

4.2 Comparison to recent schemes

The performance of the proposed scheme is compared with three of the recently proposed schemes [17, 21, 27]. The following conclusions are inferred though the comparative analysis:

(i) In the proposed paper, PMUs are required to be installed only on generator buses.
(ii) In [21], the real power output of all the generators of the system are calculated considering every candidate line as tripped, whereas in the proposed scheme tripped line can be identified by comparing the power flow of the line connected to the generator with maximum GIM following fault. Thus, the computational burden along with processing time of the proposed scheme is less compared with [21].
(iii) In [27], the fault-induced line outages are not considered and the number of PMU requirements is more compared with the proposed scheme.
(iv) The proposed scheme does not address simultaneous double line outage detection problem. Furthermore, as the suggested scheme is based on DC load flow, it may face challenges during stressed power system condition. These issues have been addressed in the recently proposed scheme in [18].
(v) The suggested method identifies tripped line in two steps. The first being identification of generator with maximum GIM. To accomplish the first task, 'GIM' information of 0.1 s is needed because normal fault clearing time is around 0.1 s (fault detection time=1 cycle and breaker operation time=4 cycle). In the next step, post-fault power flow measurement for one particular time instant is utilised to identify the tripped line. Computation time required for finding the error between the actual power flow and the estimated power flow is negligible. Thus, the whole process is accomplished within 0.2 s following fault inception. Table 10 details the comparative analysis.
(vi) PMU dynamic performance is very important for effectiveness of the proposed method, which has been demonstrated in [30] and the new findings are detailed which show compliance of the PMU/C jointly developed by Hydro-Quebec and Vizimax for WA control applications. In essence, this PMU/C meets the accuracy of class M with response time and latency of class P as specified by IEEE Standards C37.118–2011 and C37.118–2014a [30–32].

5 Conclusions

A WA measurement-based algorithm is developed for online identification of tripped transmission line. PMUs are installed at generator buses only. A new index termed as 'GIM' is used to locate the ETR of the power transmission network. Once the ETR is identified, online measured power flow of the line connected to generator having maximum GIM is compared with the estimated post-outage power flows of the same line. The post-outage power flow is estimated using the **LODF** matrix. The above power flow comparison helps in identifying the tripped transmission line. The suggested scheme is validated on New England-39 bus system and 246-bus NRPG. Simulation results show that the proposed technique can identify the tripped line with reasonable accuracy. The processing time as well as the computational burden of the proposed scheme is low compared with some of the recently suggested schemes. The findings of the research work can be utilised to improve SA which is highly essential to prevent cascaded outages in today's modern power system.

6 Acknowledgments

The first author gratefully acknowledges the technical support received from Dr. Nilanjan Senroy and Mr. Pratyasa Bhui of Indian Institute of Technology Delhi. He also acknowledges the financial support received from DST, Government of India under grant ‘Advanced Communication and Control for the Prevention of Blackouts (ACCEPT): DST/RCUK/SEGES/2012/02’.

7 References

[1] Andersson, G., Donalek, P., Farmer, R., *et al.*: ‘Causes of the 2003 major grid blackouts in North America and Europe, and recommended means to improve system dynamic performance’, *IEEE Trans. Power Syst.*, 2005, **20**, (4), pp. 1922–1928

[2] Report of the enquiry committee on grid disturbance in northern region on 30 July 2012 and in northern, eastern and north eastern region on 31 July 2012 New Delhi, India, 2012. Available at http://powermin.nic.in/upload/pdf/GRID ENQ REP 16 8 12.pdf, accessed 20 August 2012

[3] Rampurkar, V., Pentayya, P., Mangalvedekar, H.A., *et al.*: ‘Cascading failure analysis for Indian power grid’, *IEEE Trans. Smart Grid*, 2016, **7**, (4), pp. 1951–1960

[4] Dey, P., Mehra, R., Kazi, F., *et al.*: ‘Impact of topology on the propagation of cascading failure in power grid’, *IEEE Trans. Smart Grid*, 2016, **7**, (4), pp. 1970–1978

[5] Eissa, M.M., Masoud, M.E., Elanwar, M.M.M.: ‘A novel back-up wide area protection technique for power transmission grids using phasor measurement unit’, *IEEE Trans. Power Deliv.*, 2010, **25**, (1), pp. 270–278

[6] Nayak, P.K., Pradhan, A.K., Bajpai, P.: ‘Wide-area measurement-based back-up protection for power network with series compensation’, *IEEE Trans. Power Deliv.*, 2014, **29**, (4), pp. 1970–1977

[7] Jena, M.K., Samantaray, S.R., Panigrahi, B.K.: ‘A New wide-area backup protection scheme for series-compensated transmission system’, *IEEE Syst. J.*, 2017, **11**, (3), pp. 1877–1887

[8] Lim, S.I., Liu, C.C., Lee, S.J., *et al.*: ‘Blocking of zone 3 relays to prevent cascaded events’, *IEEE Trans. Power Syst.*, 2008, **23**, (2), pp. 747–754

[9] Kamwa, I., Samantaray, S.R., Joos, G.: ‘Catastrophe predictors from ensemble decision-tree learning of wide-area severity indices’, *IEEE Trans. Smart Grid*, 2010, **1**, (2), pp. 144–158

[10] Yan, J., Liu, C.-C., Vaidya, U.: ‘PMU-based monitoring of rotor angle dynamics’, *IEEE Trans. Power Syst.*, 2011, **26**, (4), pp. 2125–2133

[11] Tate, J.E., Overbye, T.J.: ‘Line outage detection using phasor angle measurements’, *IEEE Trans. Power Syst.*, 2008, **23**, (4), pp. 1644–1652

[12] Tate, J.E., Overbye, T.J.: ‘Double line outage detection using phasor angle measurements’. 2009 IEEE Power & Energy Society General Meeting, Calgary, AB, 2009, pp. 1–5

[13] Abdelaziz, A.Y., Mekhamer, S.F., Ezzat, M., *et al.*: ‘Line outage detection using support vector machine (SVM) based on the phasor measurement units (PMUs) technology’. 2012 IEEE PES General Meeting, San Diego, CA, 2012, pp. 1–8

[14] He, M., Zhang, J.: ‘A dependency graph approach for fault detection and localization towards secure smart grid’, *IEEE Trans. Smart Grid*, 2011, **2**, (2), pp. 342–351

[15] Zhu, H., Giannakis, G. B.: ‘Sparse overcomplete representations for efficient identification of power line outages’, *IEEE Trans. Power Syst.*, 2012, **27**, (4), pp. 2215–2224

[16] Wu, J., Xiong, J., Shi, Y.: ‘Ambiguity group based location recognition for multiple power line outages in smart grids’. 2014 IEEE PES Innovative Smart Grid Technologies Conf. (ISGT), Washington, DC, 2014, pp. 1–5

[17] Chen, J.C., Li, W.T., Wen, C.K., *et al.*: ‘Efficient identification method for power line outages in the smart power grid’, *IEEE Trans. Power Syst.*, 2014, **29**, (4), pp. 1788–1800

[18] Chen, Y.C., Banerjee, T., Domínguez-García, A.D., *et al.*: ‘Quickest line outage detection and identification’, *IEEE Trans. Power Syst.*, 2016, **31**, (1), pp. 749–758

[19] Huang, Q., Shao, L., Li, N.: ‘Dynamic detection of transmission line outages using hidden Markov models’, *IEEE Trans. Power Syst.*, 2016, **31**, (3), pp. 2026–2033

[20] Li, W.T., Wen, C.K., Chen, J.C., *et al.*: ‘Location identification of power line outages using PMU measurements with bad data’, *IEEE Trans. Power Syst.*, 2016, **31**, (5), pp. 3624–3635

[21] Bhui, P., Senroy, N.: ‘Online identification of tripped line for transient stability assessment’, *IEEE Trans. Power Syst.*, 2016, **31**, (3), pp. 2214–2224

[22] Wood, A.J., Wollenberg, B.F.: ‘*Power generation operation and control*’ (Wiley Interscience, New York, 1996, 2nd edn.), pp. 410–452

[23] Sobbouhi, A.R., Aghamohammadi, M.R.: ‘A new algorithm for predicting out-of-step using rotor speed-acceleration based on phasor measurement units (PMU) data’, *Electr. Power Compon. Syst.*, 2015, **43**, (13), pp. 1478–1486

[24] Rattle (the R analytical tool to learn easily), by D. Williams, ver. May 2008. Available at http://rattle.togaware.com/, accessed June 2016

[25] Pai, M.A.: ‘*Energy function analysis for power system stability*’ (Norwell, MA, USA, Kluwer, 1989)

[26] Chen, C., Wang, J., Zhu, H.: ‘Effects of phasor measurement uncertainty on power line outage detection’, *IEEE J. Sel. Top. Signal Process.*, 2014, **8**, (6), pp. 1127–1139

[27] Wu, J., Xiong, J., Shi, Y.: ‘Efficient location identification of multiple line outages with limited PMUs in smart grids’, *IEEE Trans. Power Syst.*, 2015, **30**, (4), pp. 1659–1668

[28] NRPG data. Available at http://www.iitk.ac.in/eeold/facilities/Research_labs/Power_System/NRPG-DATA.pdf, accessed 16 October 2015

[29] Fouad, A.A., Vittal, V.: ‘*Power system transient stability analysis using the transient energy function method*’ (Prentice-Hall, Englewood Cliffs, NJ, USA, 1992)

[30] Kamwa, I., Geoffroy, L., Samantaray, S.R., *et al.*: ‘Synchrophasors data analytics framework for power grid control and dynamic stability monitoring’, *IET Eng. Technol. Ref.*, 2016, pp. 1–22, DOI: 10.1049/etr.2015.0049

[31] Ghahremani, E., Kamwa, I.: ‘Local and wide-area PMU-based decentralized dynamic state estimation in multi-machine power systems’, *IEEE Trans. Power Syst.*, 2016, **31**, (1), pp. 547–562

[32] Kamwa, I., Samantaray, S.R., Joos, G.: ‘Compliance analysis of PMU algorithms and devices for wide-area stabilizing control of large power systems’, *IEEE Trans. Power Syst.*, 2013, **28**, (2), pp. 1766–1778

[33] Machowski, J., Bialek, J.W., Bumby, J. R.: ‘*Power system dynamics: stability and control*’ (Wiley, New York, NY, USA, 2008, 2nd edn.)