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Decentralised wide-area back-up protection scheme based on the concept of centre of reactive power

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Abstract: Here, a new decentralised approach-based wide-area back-up protection (WABP) scheme is proposed for faulted line identification (FLI). The scheme is divided into two sub-routines, i.e. possible faulted region (PFR) identification and FLI. Initially, the power system under study is divided into different coherent regions. The concept of centre of reactive power (CORP) is used to accomplish the task of PFR. Once the faulted region is identified, FLI is done by continuously monitoring the direction of reactive power flow (DORPF) of each line within the PFR. The proposed scheme is extensively tested on IEEE-39 bus test system for different types of faults. The performance of the scheme under stressed system conditions is also investigated. The obtained results show that the suggested algorithm is able to maintain the balance between dependability and security aspects of the protection logic.

1 Introduction

Back-up protection operation is an integral part of transmission system protection to ensure system's reliability during loss of dependability of primary protection. However, existing back-up protection scheme has the tendency to lose its security aspect during stressed power system conditions. Recent blackout reports have concluded that such mal-operations of the conventional back-up protection schemes, may have the potential to trigger cascading events leading to complete collapse of the system [1–5]. Thus, there is a dire need to develop a scheme which provides secure and dependable back-up protection to the power system.

Recently, various technological advancements in communication and mode of information sharing, as well as, integration of computer network with protection application have led to the concept of wide-area back-up protection (WABP) scheme using synchronised information from phasor measurement units (PMUs) [6, 7]. Generally, the Zone 3 operations are associated with an intentional time delay of the order of 1–2 seconds to accommodate coordination among other relays [8, 9]. Thus, the inherent latencies associated with conventional WABP scheme are not going to affect the critical clearing time of the system. In the conventional wide-area protection (WAP)-based schemes, the wide-area information is collated and processed at phasor data concentrators (PDCs) to identify the faulted region so that enhanced control decisions can be initiated [6–11]. Due to the utilisation of the wide-area information in protection applications, the relaying decisions are more reliable as compared to when taken in stand-alone configuration using local information, thus, overcoming the shortcomings of traditional scheme [10–13].

In this direction, importance of PMU information and its utilisation in WABP scheme is discussed in [3, 5]. However, need to develop dedicated and secure back-up protection to avoid Zone 3 mal-operations is suggested in [1–5]. In nutshell, Zone 3 protection scheme has been criticised for giving more weightage to its dependability attribute as compared to security attribute of the relay under stressed system conditions. Therefore, any suggested WABP scheme should enhance the security aspect of the relay without compromising the dependability aspect of the same. In this field of research, WABP scheme using sequence components of voltage and current are reported in [10–14]. Here, PMU information from all the buses of a power system is needed to locate the faulted line. Significant work is dedicated towards fault location identification in [15, 16] to review the conventional back-up protection and to adopt the recommended algorithms for the existing scheme. In [15], an adaptive back-up protection scheme is proposed to assist Zone 3 by identifying the fault location from the residual vector of a synchro-phasor state estimator (SynSE). However, sharing of huge data at all instances to a central PDC leads to communication congestion. Most of the aforementioned literatures suffer from the issues of end to end latency and data congestion. In [16], fault component voltage is estimated at one end of the transmission line using voltage and current information of the other end to identify faulty element. To facilitate faulted element identification (FEI), faulted area detection (FAD) algorithm is suggested which reduces wide-area information sharing. However, algorithm dedicated to perform FAD utilises phasor information from more numbers of PMUs. In the same line of thought, in [17], a decentralised WABP scheme is proposed. Here, the system is divided into different ‘protection zones’. Faulted line is identified using features such as ‘Gain in Momentum’, the positive sequence voltage magnitude and the change in reactive power flow.

However, the work locates the faulted element in three sequence of events, namely, vulnerable protection zone identification, bus closest to the fault identification and faulted line identification (FLI).

The current work proposes a decentralised approach-based algorithm to perform the task of PFR identification before locating the faulted line. Thus, the work accomplishes the task of FLI in two sub-routines unlike [17]. The entire power system under study is divided into different regions based on coherency study [18, 19]. PFR identification is carried out by utilising information from PMUs installed at only generator buses of each region. Limited PMU information sharing reduces end-to-end latency since the accumulation of data from majority of the substation buses has been avoided in this work. Furthermore, once the PFR is identified, a warning signal can be sent from the central load dispatch centre (CLDC) to the corresponding PFR to accomplish the task of FLI. The overall objective is to develop a WABP scheme which can identify the faulted line in the power transmission system with the ability to function appropriately under stressed system conditions.

The remainder of this paper is organised in five sections. Section 2 discusses the proposed methodology. Section 3 presents the simulation results. Validated results are discussed in Section 4. Section 5 concludes this piece of work.

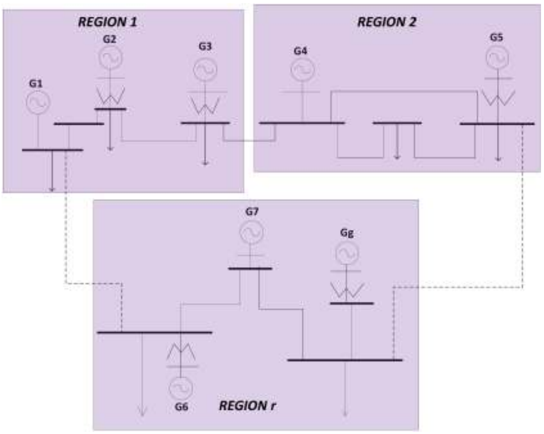

Fig. 1 *Schematic representation of a system with r region and g machines*

2 Proposed methodology

The proposed WABP architecture is structurally in accordance with the smart grid infrastructure of Indian power system. The energy management system (EMS) of its control hierarchy located at various regions is responsible for its reliable operation, control, and monitoring. It is important to understand the parallels between the proposed philosophy and the Indian power infrastructure for better realisation of the same. The Indian power infrastructure framework comprises of EMS system of national load dispatch centre (NLDC), five regional load dispatch centres (RLDCs), and state load dispatch centres (SLDCs) [20]. EMS system of NLDC is integrated with the EMS systems of RLDCs and EMS system of each RLDC in turn is integrated with EMS systems of its corresponding SLDCs. Thus, the SLDCs can act as local load dispatch centre (LLDC) of the proposed scheme, whereas RLDCs can act as CLDC.

The proposed WABP scheme comprises of two algorithms which are employed to pinpoint the faulted line in the entire system. We proceed by first introducing the concept of 'CORP voltage reference' for realising PFR identification. Once, the faulted region is identified, a warning signal is sent from CLDC to the corresponding LLDC of faulted region. Reception of the warning signal triggers DORPF algorithm which locates the faulted line with precision within the PFR. Voltages and injected reactive power of generator buses in a power systems provide significant information which can be made available using PMU infrastructure. These measurements are concentrated at CLDC of the system whose back-up scheme is developed. At CLDC, this obtained information is utilised to compute 'CORP voltage reference' which identifies not just the PFR but also differentiates between the symmetrical fault and the other stressed system conditions. Warning signal is generated only on the existence of fault in the system. The results associated with overall functioning of CORP voltage reference are validated in Section III. Next, we offer detailed description of the suggested scheme.

2.1 Concept of CORP voltage reference

The CORP voltage reference can be explained for the system given in Fig. 1. The system is divided into r regions with g number of total generator units. It is assumed that the voltage phasors and the injected reactive power information at each generator unit are provided by the PMUs.

The individual region voltage reference (IRVR) is mathematically defined as:

$$\mathrm{IRVR}_i = \frac{\sum_{k=1}^{g_i} V_k^i \, Q_k^i}{\sum_{k=1}^{g_i} Q_k^i} \tag{1}$$

where i varies from 1 to r, k and j vary from 1 to g (g_i is the gth generator in region i), V_k^i is the kth generator bus voltage in region i, and Q_k^i is the injected reactive power by kth generator unit of region i.

Unlike IRVR_i, which is calculated for each region, ESVR_T is defined as the entire system voltage reference.

Mathematically,

$$\mathrm{ESVR}_T = \frac{\sum_{j=1}^{g} V_j \, Q_j}{\sum_{j=1}^{g} Q_j} \tag{2}$$

Finally, relative voltage reference (RVR) is conceptualised for each region to identify the PFR and it is defined as the difference between ESVR_T and IRVR_i. Mathematically,

$$\mathrm{RVR}_i = \mathrm{ESVR}_T - \mathrm{IRVR}_i \tag{3}$$

where i varies from 1 to r.

The basis of this study lies in the concept of reactive power in-feed to the fault point and to the faulted region under faulty system conditions [18, 19]. Under normal system operation, the centre of reactive power (CORP) voltage reference of the regions maintain the value in sync with the entire system voltage reference. IRVR_i is the index which presents the CORP of ith region and found out to be equal to the entire system voltage reference, ESVR_T. Any deviation from ESVR_T, either positive or negative, signifies excess flow (injection/extraction) of reactive power through the particular region. RVR_i expresses the difference between ESVR_T and IRVR_i.

Mathematically, this can be understood by considering the generator bus voltages to be at their nominal values under no fault condition. Hence, by substituting $V_j = 1$ p.u. in (1) and (2) provides

$$\mathrm{ESVR}_T = \frac{\sum_{j=1}^{g} 1 \times Q_j}{\sum_{j=1}^{g} Q_j} \sim 1 \tag{4}$$

$$\mathrm{IRVR}_i = \frac{\sum_{k=1}^{g_i} 1 \times Q_k^i}{\sum_{k=1}^{g_i} Q_k^i} \sim 1 \tag{5}$$

Thus, the deviations from ESVR_T are negligible. However, when any of the region gets disturbed due to faults, this forces one or more regions to draw/inject reactive power from the system, more than it was normally drawing/injecting, to maintain their nominal voltages at generator buses.

Another important significance of RVR_i is that the regions which require excess reactive power support experiences negative RVR_i. On the other hand, the adjoining regions which provide excess reactive power to the affected regions experience positive RVR_i. This can be observed in the results shown in Section IV.

2.2 Concept of direction of reactive power flow

Once, the PFR is identified, another subroutine is made to run to precisely identify the faulted line within the PFR. This is realised using the DORPF information from each end of the transmission line within the PFR. The faulted line experiences inflow of reactive power to the fault point from both ends of the line [21]. However, non-faulted transmission lines are differentiated from the faulted ones by observing unidirectional flow of reactive power at both ends of the non-faulted lines.

In order to explain the concept of DORPF, let us consider region 2 of IEEE-39 bus test system as shown in Fig. 2. In the given figure, the pre-fault and post-fault directions of reactive power flow at both the ends of each transmission line are shown using 'blue' and 'red' arrows, respectively. If the faulted line is assumed to be 26–29, the post-fault DORPF at both ends of line 26–29 has to be opposite unlike the DORPF of the remaining transmission lines (26–28 and 28–29) within the PFR. This concept of DORPF is utilised to realise FLI post PFR identification.

3 Test cases and results analysis

The performance of the proposed WABP scheme is validated on 39-bus New England Power System using MATLAB/SIMULINK as simulation platform. Here, the main objective is to verify the dependability and security aspects of the suggested algorithm during different power system scenarios, such as faults, stable power swing, load encroachment, *(N-1)* contingencies etc. Extensive simulation studies are performed, and the results are detailed in the following subsections.

The test system is divided into six coherent regions [18, 19] as shown in Fig. 3. It is assumed that PMUs installed at the generator buses provide positive sequence voltage phasor and reactive power injection information to the CLDC. At CLDC, the RVRs of each region are monitored and the task of locating the PFR is accomplished.

3.1 PFR identification using CORP

Initially, PFR identification is executed using the proposed CORP algorithm. In order to observe the response of RVR to faulted condition, a three-phase fault with fault resistance 0.1 Ω is incepted at 50% of one of the transmission line of a region. The above-mentioned faulted condition is simulated for rest of the regions. The faulted line corresponding to each region is mentioned in Fig. 4. The figure shows response of RVRs for all the six regions. It is observed that during normal operating condition, the values for RVRs remain zero. However, following the fault inception, the PFR behaves as a sink of reactive VAR. Thus, the RVR, corresponding to the PFR, becomes highly negative. The results of CORP algorithm show that faulted region has lowest negative RVR below the threshold limit during the fault inception period. The threshold limit for PFR is assigned based on the system studies as explained in the next sub-section.

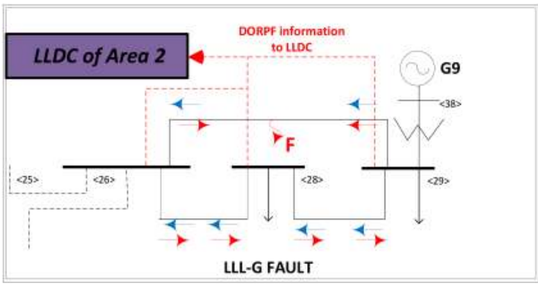

Fig. 2 *Schematic representation of DORPF algorithm for FLI*

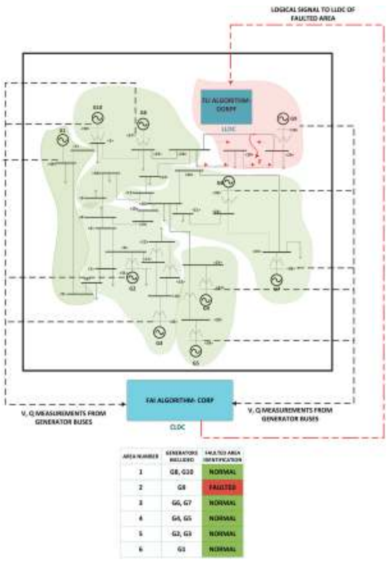

Fig. 3 *Schematic representation of proposed methodology in 39 bus New England Power System*

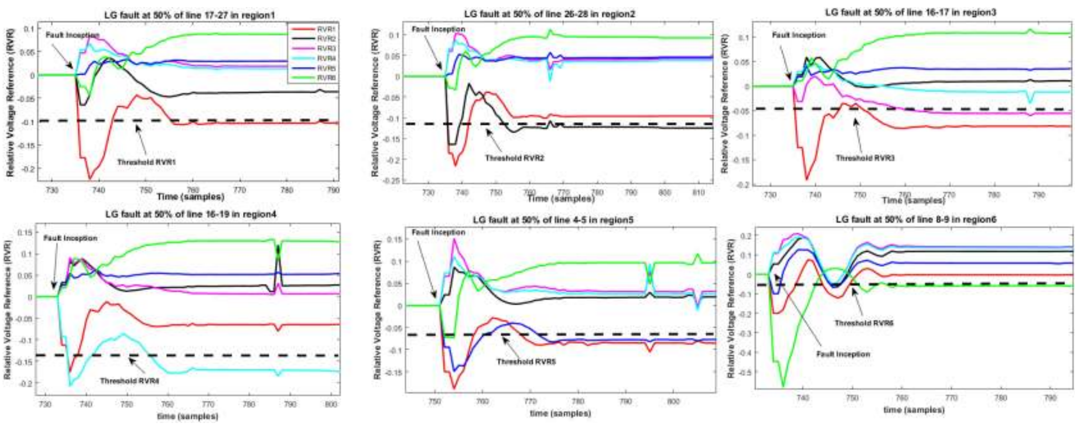

Fig. 4 *RVRs for all the six regions following LG fault*

Table 1 Threshold settings based on system studies

Region i	Location	RVR_i	Region i	Location	RVR_i
1	17–27	−10%	4	19–16	−14%
2	26–28	−12%	5	4–5	−7%
3	16–17	−5%	6	8–9	−5%

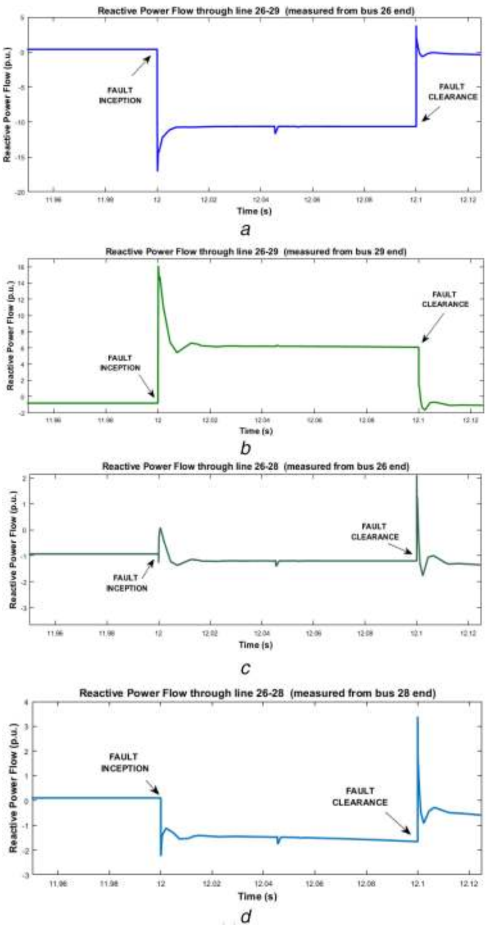

Fig. 5 *Direction of Reactive Power Flow for*
(a) faulted line 26–29 within region 2 (from bus 26), ***(b)*** faulted line 26–29 within region 2 (from bus 29), ***(c)*** non-faulted line 26–28 within region 2 (from bus 26), ***(d)*** non-faulted line within region 2(from bus 28)

3.2 Threshold determination based on system studies

The main focus of PFR algorithm is to reduce the PMU data congestion at all the LLDCs for FLI by locating the possible faulted region (PFR). If the faulted LLDC is sent the warning signal, the process would not disturb the operation at other LLDCs. However, even if the PFR algorithm sends warning signal to one or more LLDC violating the threshold, it does not alter the system configuration.

DORPF algorithm would send the final trip signal to faulted line circuit breaker only.

However, for better *selectivity of regions*, the presented work develops a methodology to determine the threshold for PFR algorithm. The threshold is developed by system studies by incepting the weakest fault farthest to the generator buses in a region. This is done to achieve a threshold value which is breached due to LG fault (and more severe faults) but not due to any other outages or stable power swing condition.

(i) All the regions of the system are incepted with L-G fault at the lines/buses which are farthest to the generator buses.

(ii) RVR_i of all the regions are monitored to find the range of deviation. Table 1 shows the range of deviations for RVR_i.

3.3 FLI using DORPF within PFR

Post-PFR identification, DORPF information is used to locate the faulted line within the PFR. The performance of DORPF is verified for all the faulted regions and the test results corresponding to region 2 is discussed below. In this region, the fault is incepted at 50% of the transmission line 26–29. Three-phase fault is incepted at 12 s and cleared at 12.1 s. In Figs. 5*a* and *b*, the reactive power flow information of the faulted line 26–29 from bus 26 and bus 29 end, respectively, is shown. During the faulty period, i.e. between 12 to 12.1 s, the polarity of DORPF from bus 26 end as well as from bus 29 end appears to be opposite as compared to the polarity of DORPF from bus 26 end and bus 28 end (on line 26–28 which is a non-faulted line). In Figs. 5*c* and *d*, the polarity of DORPF can be studied for a non-faulted line 26–28 in the PFR 2. During the faulty period, DORPF maintains negative value, showing unidirectional flow of reactive power through the non-faulted line 26–28. The given figures show that the faulted line, i.e. 26–29 acts as a sink for reactive power and thus, it experiences VAR flow from both its ends. However, in line 26–28, reactive power flow is unidirectional on both the ends. This concept assists in identifying the faulted line with accuracy.

3.4 Performance during high impedance internal fault

Sometimes, it is difficult to identify high impedance fault inceptions. However, to propose any protection scheme, it is essential to validate the dependability of the suggested scheme under such faulted system conditions. To do so, the considered test system is subjected to a three-phase fault at 50% of the transmission line 26–29 with fault impedance of 85 Ω. With such a high fault impedance, PFR identification using RVR of each region produces the results as shown in Fig. 6*a*. As seen from the figure, RVR of the faulted region (region 2) is seen to drop to −0.11, thus, crossing the suggested threshold limit to identify the fault in the system and hence, validating the successful implementation of CORP algorithm under high-impedance faulted condition. Using this information from CORP algorithm, FLI is accomplished at LLDC of the corresponding faulted region. DORPF information from all the transmission lines present in region 2 is collated at LLDC of the region. This information is analysed to realise FLI. Fig. 6*b* shows the direction of reactive power through faulted line 26–29 from bus 29 end. In the similar fashion, the DORPF through the same line from the other end (bus 26) is also shown in Fig. 6*c*. This completes the task of identification of faulted element in the system using the concept CORP and DORPF.

3.5 Performance during stable power swing conditions

Another system condition during which the conventional distance relay scheme mal-operates is stable power swing. Hence, it becomes necessary for any algorithm to give appropriate weightage to the security aspect of the back-up protection logic and take the intelligent decision during stable power swing. To test the same situation, power swing is simulated through line 26–29 after incepting a LL-G fault on line 28–29 of region 2 at 12.38 s. Circuit breakers are operated to isolate the line at 12.4 s. However, due to the line tripping of 28–29, power is transferred through the line 26–29 and hence, it experiences the power swing as observed through the response of the mho characteristics of line 26–29 (Fig. 7*a*). From the zoomed version of mho characteristics in Fig. 7*a*, it is observed that the impedance trajectory stays within the Zone 3 region for >5 ms. A, B, C, D, E, and F are the points corresponding to the parts ($T1$, $T2$, and $T3$) of impedance trajectory which are associated with 14.6609, 14.6637, 14.6876, 14.6887, 15.2167, and 15.3666 s, respectively. Encroachment of the apparent impedance into Zone 3 of conventional distance relay installed at line 26–29 may trigger relay mal-operation but it is not reflected in Fig. 7*b*, which is corresponding to the proposed algorithm of CORP. From Fig. 7*b*, it is inferred that the same region experiences fault as well as power swing but at different time intervals. During fault duration (samples 12.38 to 12.4 s) on line 26–28, RVR corresponding to region 2 crosses the threshold. However, during stable power swing through 26–29, RVRs corresponding to all the regions are marginally affected. Thus, no warning signal is sent to the LLDC during stable power swing.

3.6 Performance during load encroachment

The performance of the proposed algorithm is also verified for the load encroachment condition in the test system. Load encroachment is simulated through load scaling. Mho relay characteristics as shown in Fig. 7*c* display load encroachment taking place in Zone 3 of the distance relay corresponding to line 26–29 of region 2. Contrary to the conventional distance relay which might mal-operate in this case, CORP algorithm does not confuse load encroachment with symmetrical fault in any region as seen in Fig. 7*d*. The figure shows that RVRs of different regions are well above the threshold value which verify stable performance of the CORP algorithm during load encroachment condition.

4 Discussion

4.1 Fault on line connecting boundary buses

In real-time operation of power systems, fault can also occur on lines connecting boundary buses. Hence, it becomes imperative to suggest such a scheme which should be able to identify such faulted lines which are part of two regions and form the boundary of the connected regions in the system. Such fault locations are effectively being identified by the proposed scheme. Fig. 8*a* shows the response of RVRs of different regions when three-phase fault is incepted on the line connecting buses 8 and 9 of region 5 and region 6, respectively. As expected, following the fault inception on boundary line, the values of RVRs of region 5 and region 6 show drastic changes. However, in steady state, RVR of region 5 stays below the set threshold and thus, receives warning signal

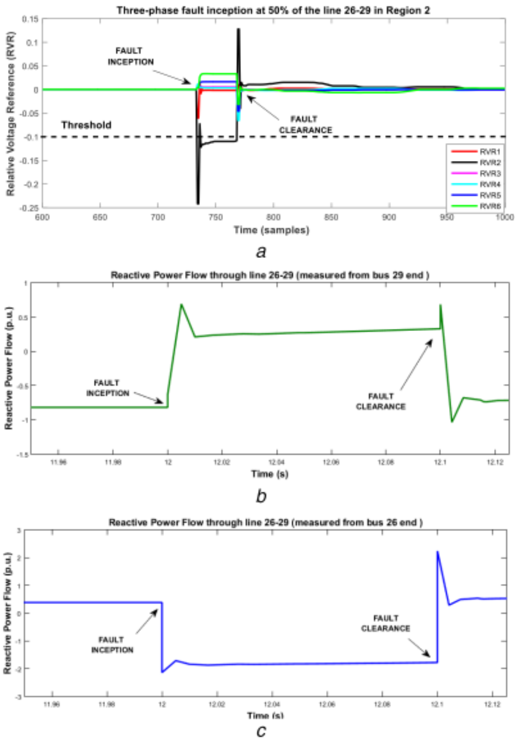

Fig. 6 *Performance validation during high impedance three phase fault*
(a) CORP voltage reference, ***(b)*** DORPF for faulted line (high impedance) 26–29 within region 2 (from bus 29 end), ***(c)*** DORPF for faulted line (high impedance) 26–29 within region 2 (from bus 26 end)

from CLDC. DORPF algorithm at LLDC of region-5 accurately locates the faulted line which happens to be between buses 8–9 in this case. Figs. 8*b* and *c* show the reactive power flow direction at both the ends of line 8–9, and it is coming out to be opposite as line 8–9 acts as the sink of reactive power.

Thus, it can be concluded that the suggested WABP scheme is reliable enough to accurately identify the faults on boundary lines.

4.2 Response time and communication issues

The PMU reporting rate is assumed to be 60 frames/s [22, 23]. We observe that if the value of RVR stays below the threshold continuously for 10 consecutive frames, a warning signal should be sent to the LLDC of corresponding PFR. The back-up protection operation is generally associated with an intentional time delay of around 1–2 s to achieve coordination [8, 9]. Further, wide-area measurement (WAM)-based technology is inherently associated with communication latency which is of the order of 100 ms [10, 14]. If we include this delay while calculating the processing time of the proposed scheme, then the response time comes out to be around 200 ms. An intentional time delay will still be included following the implementation of the proposed scheme.

4.3 Compromise of dependability

The natural question that may arise in the minds of the readers is 'whether the dependability aspect of the overall protection logic is compromised or not following implementation of the proposed scheme'? This implies that in case there is any communication failure or data loss, the functionality of the suggested scheme is affected. However, back-up protection logic operates only after mal-operations of Zone 1 and Zone 2. Thus, malfunctioning of both Zone 1 and Zone 2 along with loss of communication platform can be considered as the rarest of rare case. As a last resort, a local event detector can be employed to detect any such event which affects the dependability of the proposed scheme. In such rarest of rare case, the local event detector can override the proposed WABP logic with the conventional Zone 3 relay logic.

4.4 Compromise of security

The very purpose of introducing this piece of work is to enhance the security aspect of the back-up protection logic. Stressed system conditions such as power swing, load encroachment, (*N-1*) contingency generally induce system conditions leading to back-up protection mal-operation. While validating the proposed scheme, we tested the performance of the algorithm under such stressed system conditions. The results reveal that the suggested scheme is able to maintain security aspect of the overall back-up protection logic even during highly stressed system conditions.

4.5 Main 1 and main 2 as an alternative

When same or different types of protection schemes are used for functionally equivalent protection systems, then the overall logic is termed as main 1 and main 2 [24]. The overall dependability of the protection scheme certainly depends on the extent of independence among both the logics. However, the primary objective of the proposed research work is to enhance the security aspect of the back-up protection scheme without compromising its dependability. The simulation results show that the suggested scheme remains secure during stressed power system conditions. Thus, the proposed logic can be considered as an alternative to main 2 algorithm of the existing main 1 and main 2 protection logic.

4.6 Comparative analysis

As discussed in Sections 3.5 and 3.6, the security aspect of the proposed back-up protection scheme is tested and validated during stable power swings and load encroachment, respectively. The conventional back-up protection scheme employs concentric polygon blinder scheme, which has the power swing blocking feature. This feature takes the relaying decision depending on the

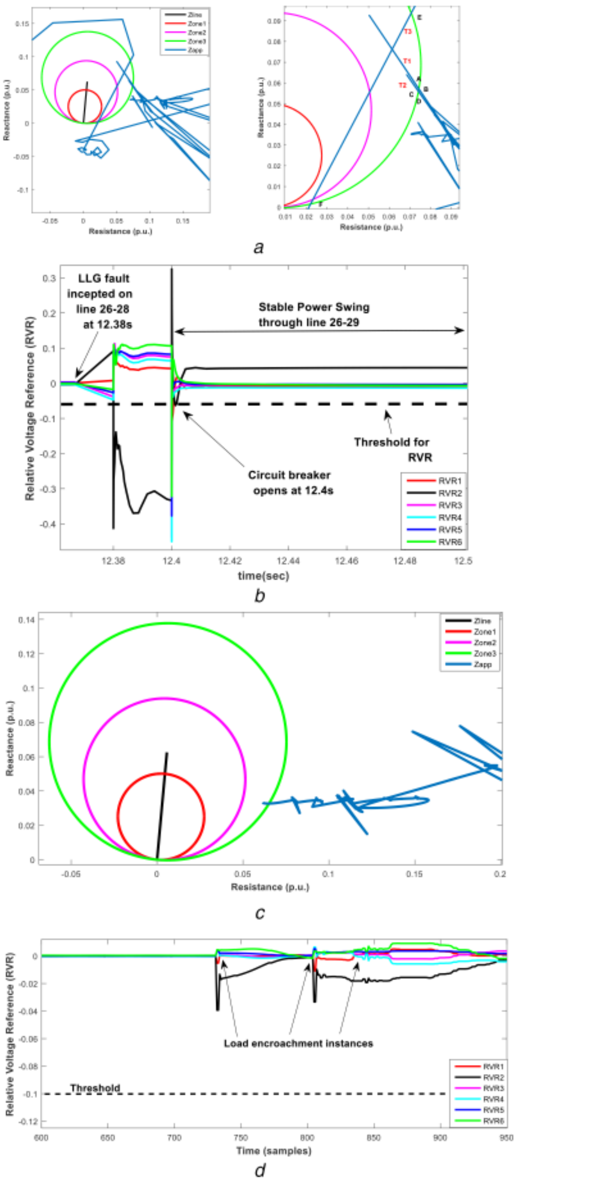

Fig. 7 *Validation of security aspect during stable power swing and load encroachment*
(a) Performance of conventional Zone 3 relay during stable power swing, ***(b)*** Performance of CORP during stable power swing, ***(c)*** Performance of conventional Zone 3 relay during load encroachment, ***(d)*** Performance of CORP during load encroachment

time taken by the trajectory of apparent impedance to travel between the two blinders, i.e. inner and outer blinders. Unlike stable power swing, in case of fault, the apparent impedance suddenly drops down to the fault impedance, and hence the travel time of the trajectory is negligible. However, the mal-operation of the conventional blinder scheme is witnessed and mentioned in various available literature during fast but stable power swing [25, 26]. In case of fast swings, the blinder scheme might lead to the mal-operation; whereas, the proposed logic performs satisfactorily and securely.

Similar observations are obtained for relay, which is placed at bus 29. Standard guidelines are followed as given in [27] to obtain the concentric blinders as shown in Fig. 9. The resistive settings are given below:

1. Right outer blinder (ROB): 0.0826 p.u.
2. Right inner blinder (RIB): 0.0743 p.u.
3. Left outer blinder (LOB): −0.0826 p.u.
4. Left inner blinder (LIB): −0.0743 p.u.
5. Angle of inclination: 84.79°.

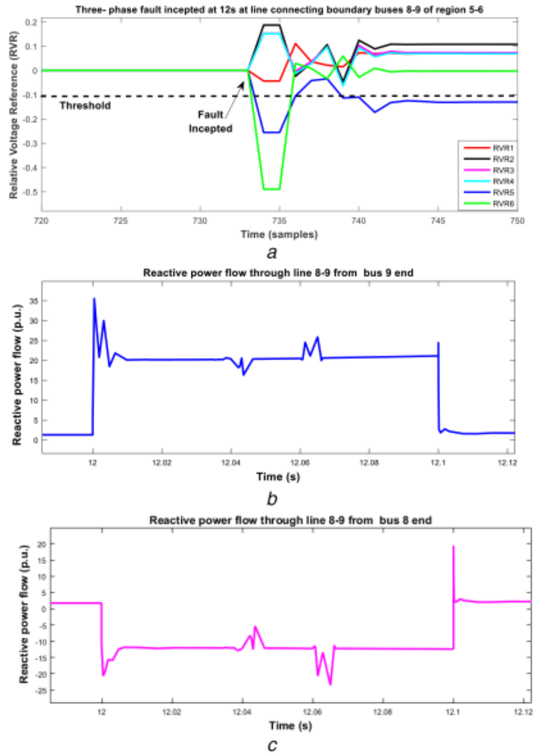

Fig. 8 *Performance of the proposed scheme during fault on line connecting boundary buses*
(a) Relative Voltage Reference characteristics, ***(b)*** DORPF for faulted line 8–9 within region 5 (from bus 8 end), ***(c)*** DORPF for faulted line 8–9 within region 5 (from bus 9 end)

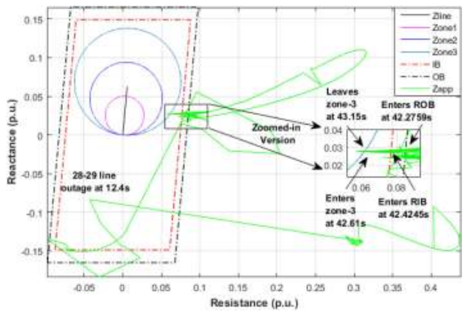

Fig. 9 *Mal-operation of blinder scheme during fast swing*

Similarly, the reactive settings are detailed below:

Outer blinder: 0.165 p.u.
Inner blinder: 0.1485 p.u.

A stable swing is observed when LLL-G fault is simulated on line 27–28 at 12 s and the corresponding breakers are operated at 12.4 s. This forces the apparent impedance trajectory seen by relay 29 of line 26–29 to enter ROB and RIB at 42.27 and 42.4245 s, respectively, which can be misinterpreted as unstable power swing by the conventional blinders in place. Similar observations are made in [9].

5 Conclusion

A WABP scheme is proposed which works on a decentralised EMS-based infrastructure. The concept of CORP is utilised to monitor RVR of each region which helps in locating the PFR within the CLDC. Further, localised execution of DORPF algorithm helps to track down the faulted line within the PFR. The scheme has been tested on IEEE 39-bus test system under various operating conditions. The suggested scheme is able to appropriately maintain dependability-security bias of back-up protection logic during normal and stressed power system conditions. Thus, with the reduction in communication latencies and data congestion owing to decentralised approach of the suggested scheme, the same can be successfully implemented in today's smart transmission grids.

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