Zonal Overcurrent Protection for Smart Radial Distribution Systems with Distributed Generation

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***Abstract*— In a smart radial distribution grid (RDS), distributed generators (DGs) will be more prominent. The addition of the DGs changes the topology of RDS, causes bidirectional power flows and contributes to fault current levels. This may result in unwanted tripping of existing overcurrent (OC) protection devices and in permanent outage of a large number of customers. The increased penetration of DGs requires a smarter protection that considers all the network flows while optimizing the system assets. This paper presents an approach that modified an existing overcurrent protection scheme to reduce the number of customers' affected by faults in RDS with DGs. The modified approach involves predefining protection zones in RDS and installing directional OC relays and circuit breakers at the zonal boundaries. Zonal boundary relays determine faulted zones by sharing information on the direction of their detected fault current using binary bit signals over a radio frequency communication medium. The approach was verified through simulations using EMTP™/PSCAD®. Results from simulations showed the selective identification and isolation of faulted zones while allowing some of the DGs to continue to supply the unfaulted parts of the system.**

***Index Terms*-- Distributed Generation, Directional Overcurrent Protection, Radial Distribution System, EMTP™/PSCAD®**

I. INTRODUCTION

In North America, most power distribution systems (DS) are designed and operated as radial circuits. The protection of these radial circuits is designed under the premise of a single power source feeding a network of downstream feeders. However, in a smart distribution grid, more distributed generators (DGs) will be connected at various locations close to loads. The addition of the DGs changes the topology of radial distribution systems (RDS) and causes bidirectional power flow. The bidirectional power flows affect overcurrent (OC) protection in RDS. Overcurrent protection practices in distribution systems involve the selective coordinated operation of many devices such as relays, reclosers, sectionalizing switches, and fuses.

Depending on the location of the DGs in the RDS, the short circuit current seen by these devices can increase or decrease thereby affecting their reach of protection. This can cause unwanted trippings and mis-coordination between the protecting devices and the protected devices on the system. Thus, the selectivity and security of OC protection systems in RDS can be greatly affected in the presence of DGs. Several researchers have dedicated significant efforts in investigating the impacts of DGs on OC protection schemes in RDS [1]-[5]. To address the array of protection complications that DG presents in RDS, researchers have proposed solutions that range from the use of fault current limiters, [6]-[7], to microprocessor reclosers [8]-[9] as well as adaptive protection schemes.

In [10]-[12] an approach is presented that minimizes the number of customers affected during faults while allowing the DGs to continue to supply the unfaulted sections of the feeder. This is achieved by dividing the distribution system into zones. The zones with DG have their load demand matched to the available generation capacity so that they can operate as intentional islands. The zoning schemes rely on one computerized central relay to control all the breakers that separate the zones.

Cyber security issues are of a major concern nowadays due to the increased dependency on computerized technology and the eventual evolution of the electric power grid to the smart grid. The reliance on the central relay can cause much harm in the event of losing the central relay due to a cyber-attack or a malfunction of the component. For example a denial-of-service attack on the central relay will produce a delay of the operating signal transmitted to the circuit breakers. Thus, it is prudent to be able to perform the same protection functions without having to rely on one central component. By decentralizing the control of the zonal breakers, this work aimed to eliminate the single point of failure that the central relay presents. This is achieved by allocating one directional OC relay per zonal breaker, and each relay shares its fault current direction information with other relays using binary state signals. The shared information is then used by the relays to decide if a trip or block signal should be issued to their respective circuit breakers.

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The paper is organized into five sections. Section II presents both the existing and modified protection schemes; section III gives details on the test system used to study the modified protection scheme; verification and performance of the modified scheme is presented in case studies in section IV. Conclusion is given in section V.

II. PROTECTION SCHEME

A. *Existing Protection Scheme*

The protection approach presented in this paper expands on the work of [10] and [11] that used a zonal concept to isolate a faulted area in RDS with DGs. The zonal concept has the property of limiting disturbances to a confined area of the network. This is essentially important in RDS where the clearance of a fault should be as selective as possible. In [11], systematic procedures for the formation of zones on a radial distribution network were outlined. The zones in [11] are formed following the steps listed below:

1. One zone is considered for each DG. A zone starts from DG bus and extends towards the end of the feeder.
2. Coverage area of a zone on the feeder continues downstream of the feeder until the DG's capacity matches the total average load within its zone.
3. In the course of a zone's expansion towards the end of the feeder for a given DG, if a second DG is encountered before exceeding the balance between the first DG's capacity and the total average load, the second DG is regarded as part of the first DG's zone.
4. A zone's coverage area is extended upwards in the event that the zone formed by the DG reaches the end of the feeder and the DG's capacity is still larger than the total average load located in the DG's zone.

Once the zones are formed, each is separated from the other using circuit breakers which are controlled by a central relay located at the substation. Each of the breakers is capable of opening and closing based on the received signals from the central relay and has a check-synchronization function. The central relay houses a look up table that is acquired through offline calculations. The table contains the current contributions from the main source and the DGs for all fault types and locations in the network as well as the current through the laterals. Online measurements of these currents are compared by the central relay to their corresponding offline values in the lookup table to help identify the faulted section and, consequently, the faulted zone. Following the identification of the faulted zone, the central relay sends tripping signals to the appropriate breakers to isolate the zone while the remaining unfaulted zones are operated as intentional islands.

B. *Modified Protection Scheme*

The modified protection scheme proposed maintains the approach for forming zones as previously discussed. However, the established zones are separated by a zonal boundary protective element (ZBE) that comprises of both a directional overcurrent (OC) relay and a circuit breaker. The directional OC element is composed of both negative and positive sequence elements. The negative sequence element operates for unbalanced faults while the positive sequence element operates during balanced faults. The control of the breakers separating the zones is decentralized by eliminating the central relay in the methods of [10] and [11].

The directional OC relays at the respective zonal boundaries control the associated zonal breaker. The individual boundary directional OC relays communicate with one another on the direction of the fault current using binary state signals. The shared fault direction information is used by the ZBEs in a directional comparison blocking scheme to decide a trip or block operation of their boundary breakers The use of binary state signals, initially proposed by [13], reduces the amount of information communicated across the channel to neighboring zonal relays. A full duplex communication channel is required so that messages can be sent independently in both directions between the ZBEs at the same time. The choice of a communication channel and channel equipment may introduce delays and that may have adverse impact on the protection and control of the ZBEs. To reduce the delays, it is suggested that a dedicated fiber optic channel be used as it has the least end-to-end delay of any communications channel and has a very low data error rate. This will also overcome the problems of ground potential rise and interference problems encountered with metallic cable.

The communication between the ZBEs must take into consideration the scale of the network as there may be redundancy in the communicated information. For instance, zones separated by two or more zones may not need to have a communication link. This is because the relays of the inner zones may have already communicated the correct fault direction information to the relays in the end zones. Two adjoining zones whose relays produce an incongruity on the direction of the fault current provide an indication of the faulted zone. This faulted zone detection is made by the relays at the boundary of the zone by utilizing the fault direction information received from the neighboring zone relays. Once a faulted zone is identified, the relays at the respective ends of the zone proceed to trip their breakers. Within a faulted zone, the local protection of the DG trips the DGs to prevent them from sourcing the fault following the tripping of the zone's breakers. This means that zones downstream of the faulted zone will be operated as intentional islands and the zones upstream of the faulted zone will be energized by the grid and any DGs that may be present.

III. TEST SYSTEM DESCRIPTION

The selected system for testing the modified protection scheme was the IEEE 34 node radial test feeder [14]. The IEEE 34 node test feeder was revised into a multi-feeder system that preserved the structure of the original test feeder. A dual bus substation configuration was adopted. For simplicity and reliability reasons, the multi-feeder was constructed as two single radial feeders that were connected by a normally opened switch at node 800. Five synchronous based DGs were introduced on the modified test feeder; three on feeder 1 and two on feeder 2. The DGs were placed both on the mains and on the 3-phase laterals of the multi-feeder. The DGs on feeder 1 were connected at nodes 840, 848 and 854. On feeder 2, the DGs were located at nodes 858 and 862. The feeder component details are given in [15].

The multi-feeder test system was divided into 7 zones following the zone procedure discussed earlier. The multi-feeder with the zone divisions is shown in Fig. 1. Four zones were formed on feeder 1 and three zones on feeder 2. Each zone was separated from the other by a ZBE comprising of the directional OC relay element and a circuit breaker. On feeder 1, the ZBEs were designated as CB1, CB2, CB3 and CB4. For feeder 2, CB5, CB6 and CB7 were the assigned description. Zones with DG had their load demand matched to the maximum available capacity of the DG. Individual ZBEs were installed at the end of the zones. The communications links are illustrated at the bottom of Fig. 1. An all-to-all communication scheme is utilized between the ZBEs.

IV. Simulation Cases and Results

The multi-feeder test system was modeled in EMTP™/PSCAD® [16]. The operating ranges of the directional elements were set as defined in the appendix. A B-C fault was applied at 4 s on the line segment between nodes 808 and 812 on feeder 2. With the fault being unbalanced, feeder 2's negative sequence directional elements of the ZBEs are analyzed. Fig. 2 shows the impedances by the negative sequence directional elements of feeder 2's ZBEs. The impedance of CB5 decreased from 2.63 Ω to -1.73 Ω during the fault. CB6 impedance value increased in magnitude to 10.31 Ω. The impedance value of CB7 also increased to a steady state value of about 16.81 Ω. Based on the measured impedances, CB5 detected a forward fault while CB6 and CB7 both detected a reverse fault. The directional status of the zonal elements is represented in Fig. 3. It is seen that CB6 and CB7 changed their active status (logical 1) from forward to reverse during the fault at about 4.05 s and CB5 active status stayed as forward during the fault. With CB5 and CB6 being the zonal protective elements that indicated opposing fault directions, they both tripped their circuit breakers to isolate zone 5, which is the faulted zone. This response is shown in Fig. 4 where both elements have their circuit breaker trip status at level "1". The tripping of CB6 also ensures that DG4 does not continue to supply the fault. Since the breaker of CB7 did not trip, zone 6 and zone 7 operated together as an intentional island.

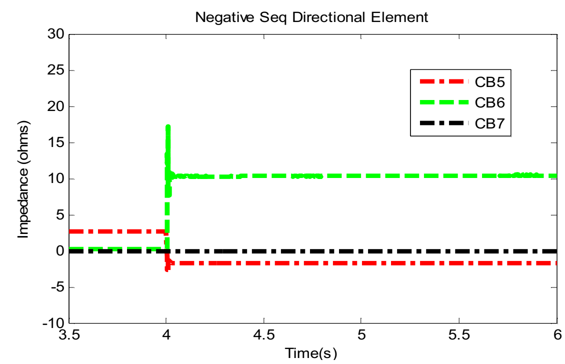

Fig. 2 Feeder 2 Zonal Boundary Elements Negative Sequence Impedance for a B-C Fault between Nodes 802-812.

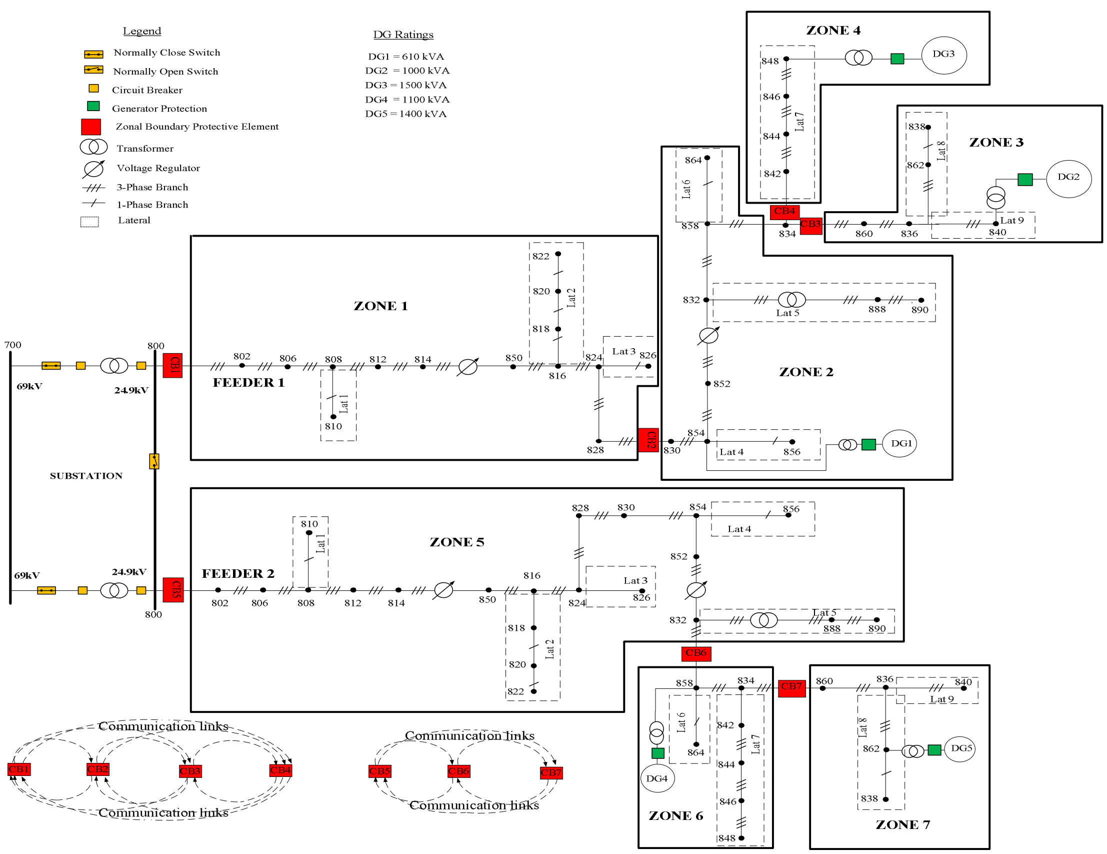

Fig. 1 Multi-feeder with zone divisions

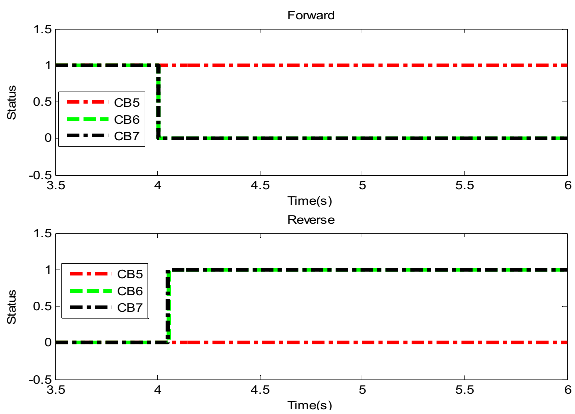

Fig. 3 Feeder 2 Zonal Boundary Elements Indicated Fault Direction for a B-C Fault between Nodes 802-812.

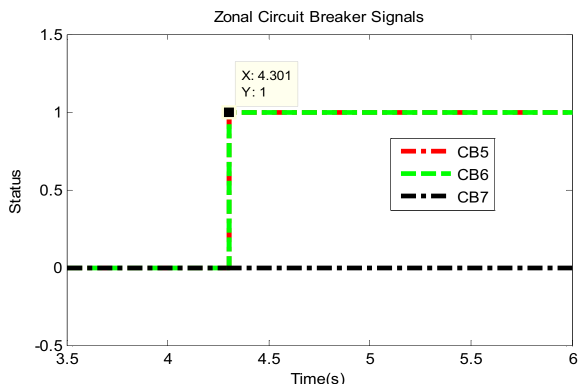

Fig. 4 Feeder 2 Zonal Boundary Elements Circuit Break Trip Status for a B-C Fault between Nodes 802-812.

A. Exhaustive Studies of Modified Protection Scheme

A series of test cases were simulated for different fault types at different locations in the zones on both feeders. The fault locations within a zone were selected to span faults on the main feeder and on laterals. Faults on the main feeder were selected to be close to the entrance of the zone, at the middle of the zone, and close to the end of the zone as possible. The results of the directional boundary relay fault detection for a number of the staged faults are summarized in Tables 1-7.

Column 1 of each table gives the line segments on which the faults were staged. Column 2 shows the fault types simulated. Column 3 indicates the monitored ZBEs negative sequence and positive sequence directional elements. The measured and expected impedances of the negative sequence directional elements of the individual ZBEs during the fault are shown in columns 4 and 5, respectively. Columns 6 and 7 provide the measured and the expected angles of the positive sequence directional elements during the fault. In columns 8 and 9, the indicated fault directions of the ZBEs are given. A "1" for either column 8 or column 9 represents the established direction during the fault. The last column shows the ZBE breakers that opened to isolate the faulted zone.

Table 1 shows some of the select fault cases in zone 1. Detailed fault studies are presented in [15]. The zonal boundary elements with one asterisk signify conditions where the measured quantity for both the positive and negative sequence elements did not corroborate each other on the fault direction. However, by letting the ultimate direction decision to be made by the appropriate sequence element based on the fault type as presented in the modified protection scheme, the correct fault direction was identified. For instance, in Table 1 an A-N fault between nodes 820 and 822 caused the negative sequence element of CB2 to indicate a reverse fault (positive impedance) while the positive sequence element detected a forward fault (angle in forward region). The erroneous indication by the positive sequence element of CB2 was due to the relatively long distance between the fault point and the DGs. Again, because the fault occurred on a single phase lateral, the substation still supplied power through the remaining healthy phases of CB2 thereby making the positive sequence element recognized the current as forward. Nonetheless, for unbalanced faults, the negative sequence element had priority over the positive sequence element thereby issuing the final direction status as reverse. The assigned priority reverses for balanced fault. Thus, for the fault type simulated between nodes 812-814, the positive sequence element had the highest priority.

Table 1 Zonal Boundary Elements Response for Zone 1 Faults

Fault Loc.	Fault Type	Zonal Boundary Elements	Negative Seq. Element Imped. (Ohms)		Positive Seq. Element Angle (Degrees)		Zonal Boundary Element Indicated Fault Direction		CBs opened
			Measured	Expected	Measured	Expected	Forward	Reverse	
820-822	A-N	CB1	-1.72	< 0	54.3	< 162. 9	1	0	CB1 CB2
		CB2*	7.24	> 1.0	50	< -17.31	0	1	
		CB3	22.11	> 0.26	-147.58	< -17.31	0	1	
		CB4	17.72	> 0.21	-76.03	< -17.31	0	1	
808-810	B-N	CB1	7.1	< 0	74.66	< 162. 9	1	0	CB1 CB2
		CB2	23.4	> 1.0	-168.24	< -17.31	0	1	
		CB3*	19.91	> 0.26	72.01	< -17.31	0	1	
		CB4	7.1	> 0.21	-118.16	< -17.31	0	1	
824-828	AB	CB1	-1.72	< 0	76.51	< 162. 9	1	0	CB1 CB2
		CB2	7.87	> 1.0	-149.06	< -17.31	0	1	
		CB3	30.36	> 0.26	-188.5	< -17.31	0	1	
		CB4	19.1	> 0.21	-129.35	< -17.31	0	1	
812-814	ABC	CB1*	2.45	< 0	49.942	< 162. 9	1	0	CB1 CB2
		CB2	1.65	> 1.0	-108.65	< -17.31	0	1	
		CB3*	0.25	> 0.26	-134.92	< -17.31	0	1	
		CB4*	0.115	> 0.21	-78.901	< -17.31	0	1	

The results for a sample of zone 2 faults are shown in Table 2. The element with double asterisks in this case represented a scenario where the priority sequence element failed to produce any change in its value for a fault within its region of operation. The AB fault in Table 2 represented such a situation. The fault type was applied on the secondary side of the in-line transformer and as a result the generation sources could not contribute much to the fault current thereby affecting the response of CB2. Nevertheless the exchange of binary bits information among the various zonal boundary protective elements on the direction of fault current ensured that the proper faulted zone was identified and eventually isolated.

Table 3 and Table 4 provide some of the fault types simulated in zones 3 and 4, respectively. Again, the elements with one asterisk indicate the case where the positive sequence and the negative sequence directional elements did not agree on the fault direction. However, depending on the fault type, the high priority directional element determined the fault direction. The double asterisks also show a scenario where the appropriate priority element failed to produce any change of its value to indicate the fault direction. Nonetheless, the fact that the installed boundary relays exchanged fault direction information allowed for the tripping of the correct zonal circuit breaker.

Table 2 Zonal Boundary Elements Response for Zone 2 Faults

Fault Loc.	Fault Type	Zonal Boundary Elements	Negative Seq. Element Imped. (Ohms)		Positive Seq. Element Angle (Degrees)		Zonal Boundary Element Indicated Fault Direction		CBs opened
			Measured	Expected	Measured	Expected	Forward	Reverse	
832-858	C-N	CB1	-1.73	< 0	76.79	< 162. 9	1	0	CB2 CB3 CB4
		CB2	-4.83	< 0	85.74	< 162.9	1	0	
		CB3	40.27	> 0.26	-180.57	< -17.31	0	1	
		CB4	21.28	> 0.21	-127.11	< -17.31	0	1	
888-890	AB	CB1	-1.75	< 0	60.17	< 162. 9	1	0	CB2 CB3 CB4
		CB2**	1.65	< 0	69.45	< 162.9	0	1	
		CB3	14.17	> 0.26	64.6	< -17.31	0	1	
		CB4	18.78	> 0.21	69	< -17.31	0	1	
832-858	AC	CB1	-1.74	< 0	77.85	< 162. 9	1	0	CB2 CB3 CB4
		CB2**	1.65	< 0	88.51	< 162.9	0	1	
		CB3	36.2	> 0.26	-225	< -17.31	0	1	
		CB4	20.38	> 0.21	-192.89	< -17.31	0	1	
830-854	ABCN	CB1*	2.45	< 0	70.36	< 162. 9	1	0	CB2 CB3 CB4
		CB2*	1.65	< 0	73.84	< 162.9	1	0	
		CB3	0.57	> 0.26	-128.88	< -17.31	0	1	
		CB4*	0.12	> 0.21	-84	< -17.31	0	1	

Table 3 Zonal Boundary Elements Response for Zone 3 Faults

Fault Loc.	Fault Type	Zonal Boundary Elements	Negative Seq. Element Imped. (Ohms)		Positive Seq. Element Angle (Degrees)		Zonal Boundary Element Indicated Fault Direction		CB opened
			Measured	Expected	Measured	Expected	Forward	Reverse	
860-836	A-N	CB1	-1.73	< 0	76.07	< 162. 9	1	0	CB3
		CB2	-4.51	< 0	82.37	< 162.9	1	0	
		CB3	-6.25	< 0	78.91	< 162.9	1	0	
		CB4	19.29	> 0.21	-124.96	< -17.31	0	1	
836-840	C-N	CB1	-1.74	< 0	76.08	< 162. 9	1	0	CB3
		CB2	-4.86	< 0	84.96	< 162.9	1	0	
		CB3	-6.89	< 0	80.95	< 162.9	1	0	
		CB4	21.24	> 0.21	-125.65	< -17.31	0	1	
860-836	AB	CB1	-1.75	< 0	74.9	< 162. 9	1	0	CB3
		CB2	-4.66	< 0	80.34	< 162.9	1	0	
		CB3	-6.31	< 0	78.79	< 162.9	1	0	
		CB4	19.2	> 0.21	-128.08	< -17.31	0	1	
836-862	BC	CB1	-1.73	< 0	77.28	< 162. 9	1	0	CB3
		CB2	-5.14	< 0	87.54	< 162.9	1	0	
		CB3	-7.08	< 0	81.94	< 162.9	1	0	
		CB4	20.46	> 0.21	-136.6	< -17.31	0	1	
834-860	ABCN	CB1*	2.45	< 0	70.42	< 162. 9	1	0	CB3
		CB2*	1.65	< 0	74..53	< 162.9	1	0	
		CB3	-0.6	< 0	55	< 162.9	1	0	
		CB4	3.94	> 0.21	-182.27	< -17.31	0	1	

Similarly, Table 5, Table 6 and Table 7 show sample fault studies for zones 5, 6 and 7, respectively. The one asterisk elements mark fault conditions where both negative and positive sequence elements indicated different fault current direction. However, the established condition for the priority of these elements based on the fault type allowed for the correct direction to be made by the relays.

In summary, the simulated fault studies shows how the modified protection scheme allows for the selective isolation of the faulted zones. For some of the simulated cases, the positive sequence and the negative sequence directional elements did not corroborate each other on the fault current direction. However, based on the assigned priority of operation of each of these elements, the correct fault current direction was indicated that allowed for the appropriate zonal circuit breakers to be tripped.

Table 4 Zonal Boundary Elements Response for Zone 4 Faults

Fault Loc.	Fault Type	Zonal Boundary Elements	Negative Seq. Element Imped. (Ohms)		Positive Seq. Element Angle (Degrees)		Zonal Boundary Element Indicated Fault Direction		CB opened
			Measured	Expected	Measured	Expected	Forward	Reverse	
846-848	A-N	CB1	-1.74	< 0	76.3	< 162. 9	1	0	CB4
		CB2	-5.08	< 0	86.53	< 162.9	1	0	
		CB3	27.19	> 0.26	-195.39	< -17.31	0	1	
		CB4	-4.46	< 0	84.48	< 162.9	1	0	
844-846	BC	CB1	-1.73	< 0	77.684	< 162. 9	1	0	CB4
		CB2	-5.18	< 0	88.47	< 162.9	1	0	
		CB3	33.34	> 0.26	-173.12	< -17.31	0	1	
		CB4	-4.86	< 0	82.94	< 162.9	1	0	
846-848	AB	CB1	-1.73	< 0	76.65	< 162. 9	1	0	CB4
		CB2**	1.65	< 0	90	< 162.9	0	1	
		CB3	28.22	> 0.26	-200	< -17.31	0	1	
		CB4	-3.78	< 0	94.8	< 162.9	1	0	
842-844	ABCN	CB1*	2.45	< 0	70.75	< 162. 9	1	0	CB4
		CB2*	1.65	< 0	74.15	< 162.9	1	0	
		CB3*	0.165	> 0.26	-200	< -17.31	0	1	
		CB4*	0.012	< 0	48.49	< 162.9	1	0	

Table 5 Zonal Boundary Elements Response for Zone 5 Faults

Fault Loc.	Fault Type	Zonal Boundary Elements	Negative Seq. Element Imped. (Ohms)		Positive Seq. Element Angle (Degrees)		Zonal Boundary Element Indicated Fault Direction		CBs opened
			Measured	Expected	Measured	Expected	Forward	Reverse	
808-810	B-N	CB5	-1.74	< 0	70.51	< 162.9	1	0	CB5 CB6
		CB6	8.55	> 0.32	-104.18	< -17.3	0	1	
		CB7	12.82	> 0.21	-237.28	< -17.3	0	1	
852-854	C-N	CB5	-1.78	< 0	72.57	< 162.9	1	0	CB5 CB6
		CB6	12.01	> 0.32	-157.36	< -17.3	0	1	
		CB7	20.54	> 0.21	-181.89	< -17.3	0	1	
808-812	AC	CB5	-1.72	< 0	79.67	< 162.9	1	0	CB5 CB6
		CB6	11.51	> 0.32	-163.96	< -17.3	0	1	
		CB7	20.85	> 0.21	-182.18	< -17.3	0	1	
888-890	ABCN	CB5*	3.42	< 0	63.71	< 162.9	1	0	CB5 CB6
		CB6*	0.27	> 0.32	-171.37	< -17.3	0	1	
		CB7*	0.67	> 0.21	-200	< -17.3	0	1	

Table 6 Zonal Boundary Elements Response for Zone 6 Faults

Fault Loc.	Fault Type	Zonal Boundary Elements	Negative Seq. Element Imped. (Ohms)		Positive Seq. Element Angle (Degrees)		Zonal Boundary Element Indicated Fault Direction		CBs opened
			Measured	Expected	Measured	Expected	Forward	Reverse	
858-864	A-N	CB5	-1.74	< 0	73.93	< 162.9	1	0	CB6 CB7
		CB6	-5.83	< 0	81.95	< 162.9	1	0	
		CB7	19.83	> 0.21	-187.44	< -17.3	0	1	
834-842	C-N	CB5	-1.75	< 0	75.16	< 162.9	1	0	CB6 CB7
		CB6	-6.41	< 0	86.87	< 162.9	1	0	
		CB7	19.56	> 0.21	-187.56	< -17.3	0	1	
846-848	AC	CB5	-1.74	< 0	74.98	< 162.9	1	0	CB6 CB7
		CB6	-6.08	< 0	83.9	< 162.9	1	0	
		CB7	19.87	> 0.21	-182.01	< -17.3	0	1	
858-834	ABCN	CB5*	3.42	< 0	69.95	< 162.9	1	0	CB6 CB7
		CB6*	0.27	< 0	51.17	< 162.9	1	0	
		CB7*	0.29	> 0.21	-108.21	< -17.3	0	1	

Table 7 Zonal Boundary Elements Response for Zone 7 Faults

Fault Loc.	Fault Type	Zonal Boundary Elements	Negative Seq. Element Imped. (Ohms)		Positive Seq. Element Angle (Degrees)		Zonal Boundary Element Indicated Fault Direction		CB opened
			Measured	Expected	Measured	Expected	Forward	Reverse	
860-836	A-N	CB5	-1.73	< 0	74.21	< 162.9	1	0	CB7
		CB6	-5.7	< 0	82.15	< 162.9	1	0	
		CB7	-4.82	< 0	89.7	< 162.9	1	0	
862-838	B-N	CB5	-1.72	< 0	71.76	< 162.9	1	0	CB7
		CB6	-6.4	< 0	84.11	< 162.9	1	0	
		CB7	-5.19	< 0	82.76	< 162.9	1	0	
836-840	AC	CB5	-1.72	< 0	75.74	< 162.9	1	0	CB7
		CB6	-6.4	< 0	82.89	< 162.9	1	0	
		CB7	-5.03	< 0	80.03	< 162.9	1	0	
836-862	BC	CB5	-1.75	< 0	75.16	< 162.9	1	0	CB7
		CB6	-6.61	< 0	88.97	< 162.9	1	0	
		CB7	-5.41	< 0	85.7	< 162.9	1	0	
860-836	ABCN	CB5*	3.42	< 0	69.5	< 162.9	1	0	CB7
		CB6*	0.27	< 0	64.4	< 162.9	1	0	
		CB7*	0.16	< 0	57.36	< 162.9	1	0	

V. CONCLUSION

The implemented protection scheme extends the zoning concept of [10] and [11] for faulted zone identification and isolation by decentralizing the control of the zonal boundary breakers. By decentralizing the control of the zone breakers, the single point of failure can be eliminated in the modified protection scheme. The scheme also eliminates the computational complexity and the high processing power needed by the central relay in detecting the faulted zone. The exhaustive faults simulated at various locations on the multi-feeder test system show how the modified protection scheme allows for selective identification and isolation of the faulted zones in a smart distribution system.

A. APPENDIX

Equation (1) shows the defined range for the forward operating region of the positive sequence element. Table 8 provides the impedance threshold set for the negative sequence element. Z2 FWD and Z2 REV are the forward and reverse impedances respectively. Table 9 indicates the direction based on the defined operating regions and the impedance thresholds for the sequence elements.

$$\frac{\pi}{2}+\theta<\beta<-\frac{\pi}{2}+\theta \qquad (1)$$

β = Angle difference between positive sequence voltage and current

θ = Line angle

Table 8 Impedance thresholds for negative sequence directional elements

	CB1	CB2	CB3	CB4	CB5	CB6	CB7
Z2FWD	2.58	0.90	0.16	0.11	3.37	0.22	0.11
Z2REV	2.68	1.00	0.26	0.21	3.47	0.32	0.21

Table 9 Fault Direction Based on Directional Element Measurement

Direction / Element	Forward	Reverse
Negative Sequence	$Z_2 < Z_2$ FWD or negative	$Z_2 > Z_2$ REV or more positive
Positive Sequence	$-17.31^0 < \beta < 162.9^0$	$\beta < -17.31^0$ or $\beta > 162.9^0$

REFERENCES

[1] K. L. Butler-Purry and M. Marotti, "Impact of distributed generators on protective devices in radial distribution systems," in *Proc. 2005/2006 IEEE PES Transmission and Distribution Conf. and Exhibition*, Dallas, TX, May 2006, pp. 87-88.

[2] T. M. de Britto, D. R. Morais, M. A. Marin, J. G. Rolim, H. H. Zurn, and R. F. Buendgens, "Distributed generation impacts on the coordination of protection systems in distribution networks," in *Proc. 2004 IEEE PES Transmission and Distribution Conf. and Exposition: Latin America*, Sao Paulo, Brazil, Nov. 2004, pp. 623-628.

[3] A. Girgis and S. Brahma, "Effect of distributed generation on protective device coordination in distribution system," in *Proc. 2001 Large Eng. Systems Conf. on Power Eng. (LESCOPE)*, Halifax, Canada, Jul. 2001, pp. 115-119.

[4] S. Kwon, C. Shin, and W. Jung, "Evaluation of protection coordination with distributed generation in distribution networks," in *Proc. 2010 10th IET Int. Conf. on Developments in Power System Protection (DPSP).* , Manchester, UK, Mar. 2010, pp. 1-5.

[5] J. A. Martinez and J. Martin-Arnedo, "Impact of distributed generation on distribution protection and power quality," in *Proc. 2009 IEEE Power and Energy Society General Meeting*, Calgary, Alberta, Jul. 2009, pp. 1-6.

[6] A. Agheli, H. A. Abyaneh, R. M. Chabanloo, and H. H. Dezaki, "Reducing the impact of DG in distribution networks protection using fault current limiters," in *Proc. 4th Int. Power Eng. and Optimization Conf.* , Selangor, Malaysia, Jun. 2010, pp. 298-303.

[7] G. Tang and M. R. Iravan, "Application of a fault current limiter to minimize distributed generation impact on coordinated relay protection," in *Proc. Int. Conf. Power Systems Transients*, Montreal, QC, Canada, Jun. 2005.

[8] S. M. Brahma and A. A. Girgis, "Microprocessor-based reclosing to coordinate fuse and recloser in a system with high penetration of distributed generation," in *Proc. 2002 IEEE Power Eng. Soc. Winter Meeting*, New York, USA, Jan. 2002, vol. 1, pp. 453-458.

[9] A. Zamani, T. Sidhu, and A. Yazdani, "A strategy for protection coordination in radial distribution networks with distributed generators," in *Proc. 2010 IEEE Power and Energy Society General Meeting*, Minneapolis, MN, USA, Jul. 2010, pp. 1-8.

[10] S. M. Brahma and A. A. Girgis, "Development of adaptive protection scheme for distribution systems with high penetration of distributed generation," *IEEE Trans. Power Delivery,* vol. 19, pp. 56-63, Jan. 2004.

[11] S. A. M. Javadian and M. R. Haghifam, "Implementation of a new protection scheme on a real distribution system in presence of DG," in *Proc. 2008 POWERCON and IEEE Power India Conf. on Power System Technology*, New Delhi, India, Oct. 2008, pp. 1-7.

[12] S. A. M. Javadian, R. Tamizkar, and M. R. Haghifam, "A protection and reconfiguration scheme for distribution networks with DG," in *Proc. 2009 IEEE PowerTech Bucharest*, Bucharest, Romania, Jun. 2009, pp. 1-8.

[13] K. Okuyama, T. Kato, Y. Suzuoki, and T. Funabashi, "Protection relay system using information network for distribution system with DGs," *Electrical Engineering in Japan,* vol. 155, pp. 1281-1285, Apr. 2006.

[14] W. H. Kersting, "Radial distribution test feeders," in *Proc. 2001 IEEE Power Engineering Soc. Winter Meeting*, Columbus, OH , USA, Jan. 2001, vol. 2, pp. 908-912.

[15] F. A. Ituzaro, "A technique to utilize smart meter load information for adapting overcurrent protection for radial distribution systems with distributed generation," MSc. thesis, Dept. of Electrical and Computer Eng., Texas A&M University, 2011 in press.

[16] "EMTP/PSCAD," Manitoba HVDC Research Centre Inc.

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