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Fault detection and location algorithm for DG-integrated distribution systems

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Abstract: The overcurrent protection on the traditional distribution system uses local measurements and settings as a basis for decision-making. However, connection of multiple distributed generators with different short-circuit characteristics makes the local measurements unpredictable, leading to possible loss of protection coordination. In order to solve this problem, this study proposes an algorithm that achieves its protection function through load flow and sensitivity calculations based on voltage measurements. The algorithm is built on a modelling approach that splits the distribution network into a series of overlapping protection zones. The overlapping feature is realised logically through peer-to-peer communications between intelligent agents located in adjacent zones. A sensitivity-based electrical signature was identified that is generated when a fault occurs within a zone. Simulation results show that the proposed protection algorithm is able to identify the zone in which the fault has occurred and the specific faulted node or line section in that zone. The fault current contributions, or no contributions, of the distributed generators (DGs) do not impact the operation of this algorithm.

1 Introduction

The increasing connection of distributed generators (DGs) to the distribution system has brought about many technical challenges including protection. The existing protection on the traditional distribution system is based on predictable unidirectional current flows. The stand-alone protection devices use local measurements and settings as a basis for decision-making. However, connection of different types of DGs makes the local current magnitude measurements unpredictable [1, 2] and the applied protection settings become invalid, leading to possible loss of coordination [3, 4].

A wide range of strategies have been proposed in the literature to mitigate the impact of DG integration on distribution system protection. The work presented in [5] attempts to minimise the changes in fault current levels by minimising the change in the bus impedance matrix for each possible system state through optimal planning (location and size) of the resistive–inductive–capacitive fault current limiters, thereby maintaining short-circuit levels and the relay settings. Optimal sizing and location of DGs strategies as reported in [6, 7] attempt to minimise the impact of DG connection on the protection settings and fuse sizes.

Adaptive protection schemes have also been proposed [4, 8, 9] that require the protection settings to adapt to the prevailing system state that depends on the DGs status – whether connected or disconnected. Adaptive schemes that use multi-agent systems (MAS) have also been proposed [10–12]. MAS systems avoid or mitigate the impact of different kinds of failure, including communication failure, and ensure correct adaptive operation of the protection.

Impedance and admittance-based methods have been proposed for application at the distribution level [13, 14]. However, the connection of DGs at multiple locations creates problems of in-feeds that may cause the impedance relays to under-reach [15]. Additionally, this method may not function correctly with inverter-interfaced DGs that limit the fault current to a fixed level [16].

Artificial intelligence methods have been proposed that analyse information and patterns generated by techniques such as principal component analysis [17, 18] and wavelet analysis [19, 20] to identify and locate faults.

Research efforts are reported in the literature that attempt to influence the inverter design and control in order to enable inverter-interfaced DGs to contribute short-duration fault current sufficient to aid the detection of faults [21–23]. However, the inverter control required for protection is in conflict with that required to give the DG FRT capability [24–26]. The FRT capability ensures the power system's post-fault stability and fast recovery [27–29].

Protection techniques based on voltage measurement have been reported and have potential to overcome the challenges of protecting distribution networks integrated with multiple types of DG, including inverter-interfaced DG. Researchers in [30, 31] proposed protection schemes which apply modal transformations on the measured system voltages. Any disturbance resulting from short-circuit fault condition is reflected as a disturbance to the DC *d–q* values when compared with the reference values with no fault. The use of the total harmonic distortion (THD) of a DG unit's point-of-coupling voltage is proposed in [32] as a tool for detecting faults. However, it is established in [33] that protection discrimination through THD may be difficult.

A wide body of research is reported on the use of travelling waves (TW) for the detection and location of faults. TW fault detection methods have been developed for the transmission system [34] and have also been proposed for the distribution system in [35–37]. The research results are promising, but some challenges still persist with regard to the implementation technologies. The voltage transformers (VTs), at the current state of technology, are not suited for the measurement of high-frequency transients without additional measures, because of limited bandwidth [38]. Research on the development of non-conventional instrument transformers is ongoing. The non-conventional VTs promise to provide better accuracy, transient response, and wider bandwidth compared to the conventional VT for the future grid [39].

This paper proposes a new protection algorithm that achieves its protection function through load flow and sensitivity calculations based on voltage measurements only. The algorithm is built on a modelling approach that splits the distribution network into a series of overlapping segments. The protection algorithm identifies a ‘unit’ segment over which it monitors power flows. A fault signature is generated when a ‘leakage’ or fault occurs within this segment causing power flow imbalance. Through peer-to-peer communications, the protection algorithm is able to identify the

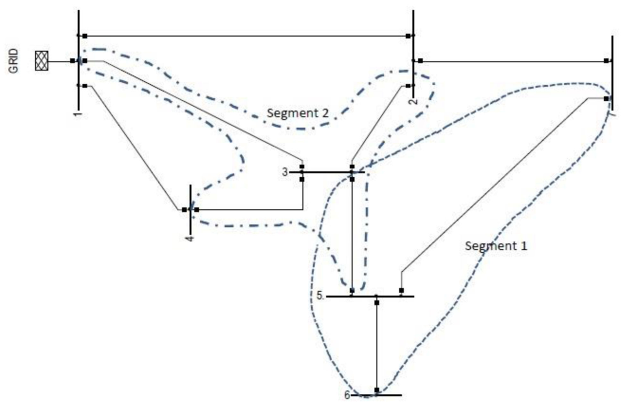

Fig. 1 *Protection zones of the proposed algorithm*

'unit' segment in which the fault has occurred and the specific faulted node or line section in that segment.

This paper is organised as follows: Section 2 gives the background theory of the proposed protection algorithm. Simulation results and discussion to evaluate the performance of the algorithm are given in Section 3. The conclusions are given in Section 4.

2 Proposed fault detection algorithm

The proposed algorithm is built on a modelling approach introduced in [40] that splits the distribution network into a series of overlapping segments or 'units', as illustrated in Fig. 1. A 'unit' segment (or protection zone in this context) consists of a 'home' node and its neighbouring nodes only. Fig. 1 shows two of the segments of a seven-bus network; segment 1 consists of node 5 and its neighbouring nodes 3, 6, and 7; segment 2 is centred at node 3. Other segments can be added centred at each node. The overlapping feature is realised logically through intelligent agents (in the form of intelligent electronic devices, IEDs) located in each segment (at the 'home' node) that exchange information with the agents in the adjacent segments.

The load flow at the 'home' node k of a segment with N nodes can be expressed as [40]

$$P_k = V_k^2 Y_{kk}\cos(-\delta_{kk}) + \sum_{j=0}^{(k+1)_{N-1}} V_k V_j Y_{kj}\cos(\delta_k - \delta_j - \delta_{kj}) \tag{1}$$

$$Q_k = V_k^2 Y_{kk}\sin(-\delta_{kk}) + \sum_{j=0}^{(k+1)_{N-1}} V_k V_j Y_{kj}\sin(\delta_k - \delta_j - \delta_{kj}) \tag{2}$$

where P_k and Q_k are the real and reactive power flow at node k; V_k and δ_k, respectively, the voltage magnitude and angle at node k; V_j and δ_j the voltage magnitude and angle at node j; Y_{kj} and δ_{kj}, respectively, the magnitude and argument of the element (k, j) in the network's admittance matrix.

Now, the neighbouring nodes are one node away from the 'home' node. In other words, the neighbouring nodes are within $(k \pm 1)$ range of the home node, irrespective of the number of these neighbouring nodes. The admittance matrix of the network shows that

$$Y_{kj} = 0 \quad \text{if} \quad j < (k-1) \text{ or } j > (k+1) \tag{3}$$

Hence, the summation range is shown in (1) as $(k+1)_{N-1}$ simply to indicate that the $(N-1)$ neighbouring nodes are within $(k \pm 1)$ range of node k.

Changes in P and Q are related to changes in voltage by the partial differential equations [40]

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}\dfrac{\partial P}{\partial \delta} & \dfrac{\partial P}{\partial V}\\ \dfrac{\partial Q}{\partial \delta} & \dfrac{\partial Q}{\partial V}\end{bmatrix} \cdot \begin{bmatrix}\Delta \delta\\ \Delta V\end{bmatrix} = \left[\boldsymbol{J}_{PQ\delta V}\right] \cdot \begin{bmatrix}\Delta \delta\\ \Delta V\end{bmatrix} \tag{4}$$

$\left[\boldsymbol{J}_{PQ\delta V}\right]$ is the Jacobian matrix of the network. The elements of the Jacobian matrix give the sensitivity between power flow and bus voltage changes.

From (4), the change in active and reactive power at node k (of the unit segment or protection zone as described in this paper) may be expressed as

$$\Delta P_k = \frac{\partial P_k}{\partial \delta_k}\Delta\delta_k + \sum_{j=0}^{(k+1)_{N-1}} \frac{\partial P_k}{\partial \delta_j}\Delta\delta_j + \frac{\partial P_k}{\partial V_k}\Delta V_k + \sum_{j=0}^{(k+1)_{N-1}} \frac{\partial P_k}{\partial V_j}\Delta V_j \tag{5}$$

$$\Delta Q_k = \frac{\partial Q_k}{\partial \delta_k}\Delta\delta_k + \sum_{j=0}^{(k+1)_{N-1}} \frac{\partial Q_k}{\partial \delta_j}\Delta\delta_j + \frac{\partial Q_k}{\partial V_k}\Delta V_k + \sum_{j=0}^{(k+1)_{N-1}} \frac{\partial Q_k}{\partial V_j}\Delta V_j \tag{6}$$

Equations (5) and (6) are the non-decoupled equations describing the *P*–*Q*–*V*–*δ* relationship for the unit segment.

Manipulation of (5) and (6) reveals a sensitivity function S_k whose magnitude depends on changes in the voltage and power injection at the node (k) following fault occurrence, thus

$$S_k = Fn(\Delta V_k, \Delta P_k) \tag{7}$$

S_k is calculated at each node of the network. Using voltage phasor measurement units, the IED running this algorithm takes the synchronised voltage measurements from the local and neighbouring nodes as inputs. Considering segment 1 in Fig. 1, for example, the relay located at node 5 takes the voltage measurements from node 5 as well as nodes 3, 6, and 7. The algorithm performs load flow and sensitivity calculations over the specific protection zone (or segment) to determine ΔP_k and S_k. When the power flowing into the protection zone equals the power flowing out, the function S_k takes a value equal to zero. However, S_k is non-zero when there is a 'leakage' or fault within the segment causing power flow imbalance. This sensitivity function can thus be regarded as an electrical signature that is generated when a fault occurs within the respective unit segment.

Through peer-to-peer communications between the IEDs located at each node in the network, the protection algorithm is able to identify the 'unit' segment in which the fault has occurred and the specific faulted node or line section in that segment. This functionality is similar to that in distance protection schemes where one relay sends a request to trip to the relay at the remote end of the feeder. The remote relay trips its circuit breaker having also detected the fault.

Connection or disconnection of load can also generate the fault signature. However, experimental results show that the magnitude of the signal under normal system operations is much smaller compared to that generated by fault over a wide range of fault resistances. A threshold can thus be set above which S_k indicates fault condition.

3 Results and discussion

The generation of the fault signatures is demonstrated through simulations. The simulations are performed using Digsilent PowerFactory software on the modified IEEE 34-node test network illustrated in Fig. 2.

The modified and re-numbered network was adapted from the original network available at [41]. The two voltage regulators between nodes 5–6 and 12–13 in the original network have been

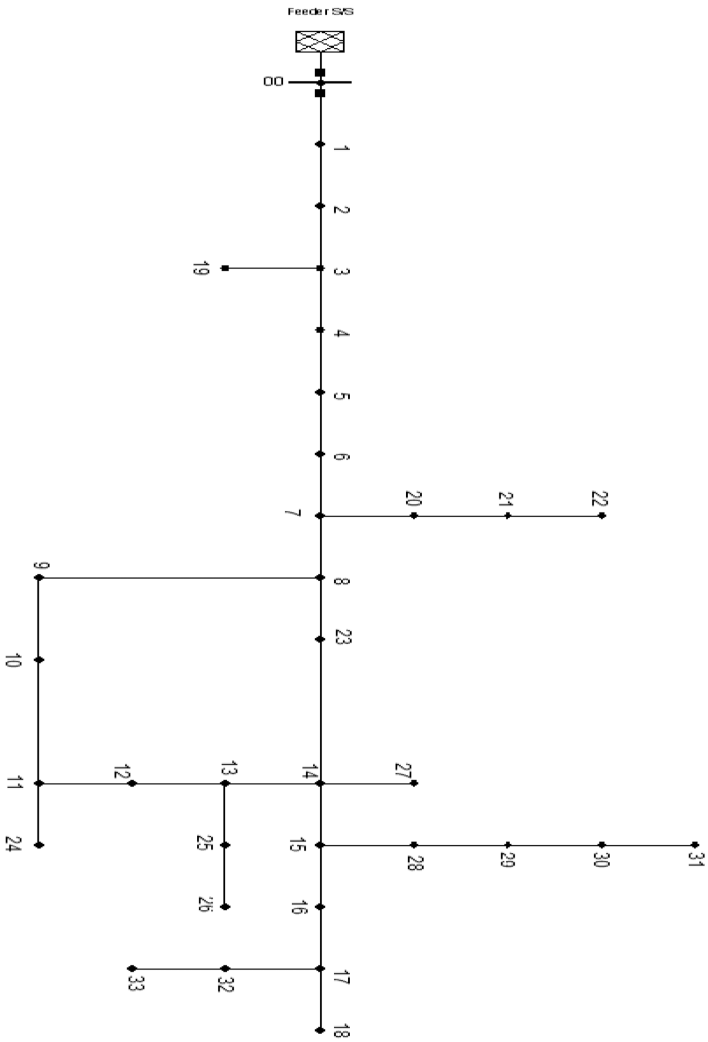

Fig. 2 *Modified IEEE 34-node test system (adapted from [41])*

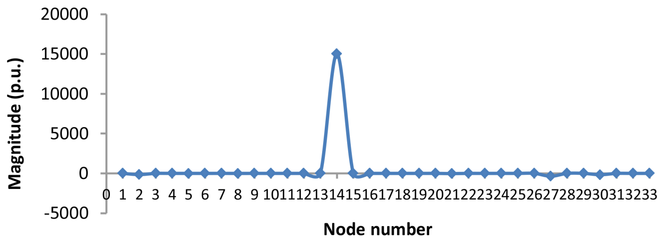

Fig. 3 *Fault signatures with phase-to-ground fault at node 14*

bypassed. A mesh is also introduced by connecting a tie-line between nodes 14 and 23, creating a single mesh in the network. This is to allow the effectiveness of the proposed algorithm to be tested on the radial as well as meshed sections of the network. Three small distributed wind farms each rated 4.6 MW are connected at nodes 21, 27, and 30.

Various types of faults were simulated at different locations in the network and the fault signatures were calculated at each node. The results shown in Figs. 3–6 are representative of the fault signatures generated for faults at any point in the network.

A fault is simulated at node 14 and the S_k values are calculated at each node of the network. The results are shown in Fig. 3. It can be seen that a fault signature is generated only at node 14 indicating fault occurrence at that node. Everywhere else the S_k values are insignificant. Fig. 4 shows the results for a phase-to-phase fault. A significant spike can be seen at node 14 indicating fault at that node. The fault signatures on the healthy phase at all nodes for this fault are seen in Fig. 5. The signature magnitudes are of the order of 10^{-12} and may be regarded as noise. No fault is detected anywhere on this phase as the values are well below the threshold.

The results for a fault at the mid-point of feeders 14–23 are shown in Fig. 6. It can be seen that two fault signatures are generated at the two nodes at the ends of the feeder. These are detected by the respective IEDs. The neighbouring IEDs share information through peer-to-peer communication and when both detect a fault it means that the fault is somewhere along the feeder section between them. Work is in progress to enable the proposed algorithm to determine the distance to the fault from either of the two adjacent nodes. The algorithm thus implements a unit protection scheme and is able to achieve fast fault clearance times. Hence, this algorithm is suitable for the modern and still evolving power system that incorporates numerous DGs requiring faster protection systems for enhanced power system stability.

The algorithm is confined to a specific segment (protection zone) over which it is responsible, and so does not see the structure of the network beyond the neighbouring node(s) in this protection zone. The electrical fault signature is generated only when power flow imbalance, caused by fault, occurs in the respective zone. It

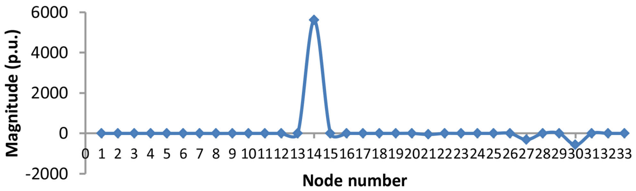

Fig. 4 *Fault signatures with phase-to-phase fault at node 14*

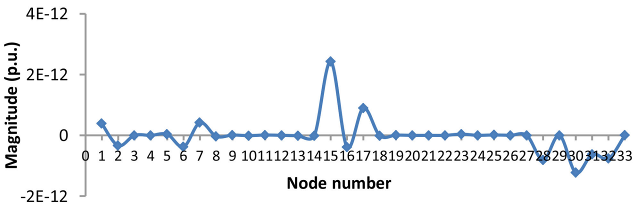

Fig. 5 *Fault signatures on healthy phase with phase-to-phase fault at node 14*

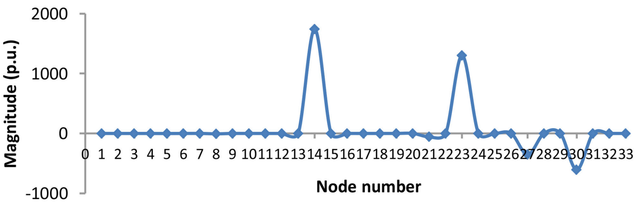

Fig. 6 *Fault signatures with phase-to-phase fault at mid-point of feeders 14–23*

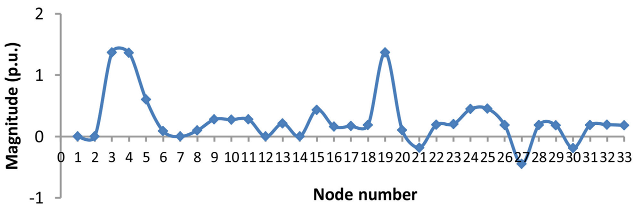

Fig. 7 S_k *signatures resulting from connection of loads and DGs*

does not matter what source, conventional or RES, are feeding the fault. The network might have multiple DG types connected, but this will not impact the performance of the proposed algorithm. The simulation results show that the algorithm is able to identify the unit segment in which the fault has occurred, and the specific node or line section that has been faulted irrespective of fault type. The algorithm is applicable to radial or meshed distribution networks.

Negative fault signatures can be observed at nodes 21, 27, and 30 in Figs. 4 and 6. These are the nodes at which DGs are connected. Fault causes voltage disturbance in the network and this impacts the power delivered by the DGs. Hence, the drop in output power at the DG node is seen as a negative change in power and manifests as a negative fault signature.

Fig. 7 shows the signatures generated by connection of load at the various nodes. The signature magnitudes due to the loads are seen to be positive but much smaller compared to those due to fault. The pick-up threshold is positive and the negative spikes due to DG connection are ignored and will not be picked up. It can also be observed that no loads are connected at nodes 7, 12, and 14.

4 Conclusion

This paper has proposed a new algorithm that provides fast and selective clearance of faults, irrespective of fault type, in a distribution system. The algorithm uses a modelling approach that splits the distribution system into a series of overlapping segments and is able to identify the segment in which the fault has occurred and the specific node or line section in that segment. The algorithm is shown to be effective when applied to radial and meshed networks. The algorithm shows that protection techniques based on voltage measurement have potential to overcome the challenges of protecting distribution networks integrated with multiple types of DGs, including inverter-interfaced DGs.

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