Synchronous Distributed Generation Fault Interconnection Detection Using Intelligent Relays

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Abstract

With the increasing environmental concerns and state regulatory pressure, Distributed Generators (DGs) are becoming more common in the Electric Power distribution networks. The integration of distributed generation into distribution feeders, however, presents many challenges an important one being the DG Fault Interconnection protection. The role of the DG Fault Interconnection is to prevent faulted DGs from contributing fault currents to an area-EPS fault, contributions that could threaten the existing distribution system infrastructure. This concern makes standing DG Interconnection guidelines to require that the DG Fault Interconnection Protection detects all feeder faults and disconnects the DG(s) as soon as possible. This work is undertaken under the assumption that no Voltage Ride Through (VRT) requirements apply, a concern applicable to DGs exceeding 10 MVA and normally connected to subtransmission type meshed systems and not to radial distribution feeders as this work assumes.

This thesis addresses this immediate DG disconnection needed upon an area-EPS fault inception, by proposing an Intelligent Relay (IR) that detects feeder shunt faults, anywhere within the geographical span of the considered feeder and of various degrees of severity. DGs of the synchronous type are treated here due to the vast popularity they still enjoy as a well understood and supported technology. The fault detection IR is set using data mining methods that produce Decision Trees (DT) encapsulating the relay tripping logic and thresholds. It is also demonstrated hereinafter that the same techniques can be used to serve relay recording purposes through identifying both the type of the incipient shunt fault as well as the implicated faulted phases. The applicability of the technique is demonstrated for one and for several synchronous DGs operating in parallel on a medium-voltage balanced distribution test-bench feeder. The IR settings have been programmed on an actual commercial relay and results on the Real Time Simulator using the IR as a Playback Hardware in the Loop (HIL) corroborated the validity of the approach.

Résumé

Pour les raisons concernant l'environnement et la pression des règlements d'état, les générateurs distribués (DGs) deviennent de plus en plus répandus dans les réseaux de distribution électrique. L'intégration de la génération distribuée dans les réseaux de distribution, néanmoins, représente plusieurs défis technologiques. Parmi ceux-ci, une importante est la protection pour les défauts d'interconnexion. Le rôle de la protection DG contre les défauts est de prévenir les DGs en panne de contribuer les courants de défaut au default du 'area-EPS'. Cette notion établit les règlements courants d'interconnexion des DGs d'assurer que la protection DG contre les défauts d'interconnexion soit capable de détecter toutes les fautes du réseau et de déconnecter les DGs le plus vite possible. Dans ce travail on suppose que les règlements lors d'un sous tension (Voltage Ride-Through) ne s'appliquent pas, parce que la notion de VRT s'applique aux DGs au-dessus de 10 MVA qui sont normalement connectés aux réseaux de type 'meshed' et non des réseaux de type 'radial', comme décrit dans ce travail.

Cette thèse s'adresse au nécessité de déconnexion immédiate des DGs après un défaut 'area-EPS', en proposant un relais intelligent qui détecte les défauts en parallèle n'importe quel endroit géographique du réseau considéré et de toutes degrés de sévérité. Les DGs de type synchrone sont traités ici, et à cause de leur vaste popularité ils profitent toujours du support comme une technologie bien comprise. Le relais intelligent pour la détection de défauts est programmé en utilisant les méthodes d'exploration de données, qui produisent les arbres de décision contenant la logique de déclenchement du relais et ses niveaux de sensibilité. Le degré d'application de cette technique et montré pour un seul et pour plusieurs DGs synchrones fonctionnant en parallèle sur un réseau de distribution balancé de moyenne tension. Les paramètres du relais intelligent ont été programmés dans un relais commercial et les résultats obtenus avec la connexion du relais intelligent avec un simulateur à temps réel ont contribué à la validité de cette recherche.

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There are many amazing and wonderful people I would like to acknowledge in this section, those without whom I would not be here, who provided me support and guidance, those I frequently consulted during my degree, and lastly those who made living in Montréal a memorable experience. But first and foremost, I thank my parents and my sister, Karan, for their relentless support and always being a source of encouragement. I am very humbled to have Prof. Géza Joós accept me as his student. His guidance, support, and opportunities he provided are greatly appreciated. I have gained more sound understanding of the power systems under his supervision allowing me to start making contributions to the power industry in a meaningful way. I would also like to acknowledge the assistance and supervision provided by Dr. Anthony J. Rodolakis. I thank him for providing assistance in editing the manuscript of this thesis and the papers we wrote together. In addition, the support provided by Yves Brissette and Chad Abbey is greatly appreciated. I acknowledge the financial support provided by NSERC through the NSERC/Hydro-Qubec Industrial Research Chair on the Integration of Renewable Energies and Distributed Generation into the Electric Distribution Grid, held by Professor G. Joos. I sincerely thank my labmates Shijia Li, Farah Awan, Samah Mansour, Martine Chela, Dmitry Rimorov, Qiushi Cui, Diego Mascarella, Howard Jiang, Michael Ross, Alexey Sokolov, Juan Clavier, Omar Saadeh, Navdeep Dhaliwal, Subhadeep Bhattacharya, Syed Ali, Saravan Khumar, Sijie Qin, Debi Mishra, Elie Hinain, Ali Jahanbani Ardakani, Moataz Ammar, Amir Kalantari, Amir Abiri, Abut Hadd, Ali Shoja, Mike Quashie, and all others. I acknowledge Michael Ross for making his LATEX template available to me. I also thank to have friends Jigar Patel, Erika Janitz, Alireza Samani, Victor Yeung, Mahmoud Tabieh, Dhruv Patel, Skanda Shridhar, Nathan Mak, Leon Chen, Omar Saeed, Marcos Clavier, Zhe Cui, Farhan Khan, Kishen Pais, and everyone I have missed here.

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Chapter 1

Background and Thesis Outline

1.1 Introduction and Scope

Environmental concerns, state regulations and the tendency to decentralize power generation by capitalizing on the availability of renewable generation technologies led to the increasing penetration of Distributed Generators (DGs) in the Electric Power distribution networks. Integrating distributed generation, of any technology vintage, presents significant challenges to the operation and the protection of distribution systems since both steady state and fault currents originating from the DGs must now be accounted for. In terms of distribution feeder protection, new issues arising from the presence of DGs affect both the utility feeder protection and the DG itself and they originate from either DG islanding or area-EPS faults, as discussed subsequently.

This thesis is not concerned with the utility perspective of distribution feeder protection but focuses, instead, on DG Fault Interconnection Protection. Since detecting an area-EPS fault is paramount in achieving rapid DG disconnection under fault conditions, it becomes clear that distribution faults of any type and severity must be duly detected by the DG Fault Interconnection Protection, anywhere within the distribution feeder the DG is connected at.

The first focal point of this thesis therefore is to propose an Intelligent Relay (IR) that detects area-EPS faults of the shunt type, i.e. Three-Phase (LLL) , Single Line to ground (SLG), Line to Line (LL), and Double Line to Ground (LLG) of any reasonable severity anywhere within the feeder, based on first cycle RMS fault currents information as sensed by the DG Interconnection Protection. The proposed IR is a passive protective device, set using Data Mining methods and it requires the same type of information currently used by conventional DG Fault Interconnection Protection devices, thus imposing no extra infrastructure costing.

The second focal point of this thesis is to show that the proposed IR can also credibly accomplish recording tasks, under fault conditions, in achieving not only shunt fault type recognition but identify the implicated faulted system phases as well.

The third focal point of this thesis is to compare the performance of the proposed IR to the like performance of other conventional protective devices currently used for Fault Interconnection Protection duty.

The fourth focal point of this thesis is to demonstrate the feasibility of using the proposed IR by programming an actual commercial microprocessor relay using the techniques described therein and integrate it as a Hardware in the Loop (HIL) application in a Real Time Simulation (RTS) environment.

1.2 Distributed Generation Penetration Evolution

Power systems have evolved a lot since the first commercial use of AC Transmission in 1886. In the early 1900s, power was mainly provided through small isolated generators to customers located in close proximity to them. As power began to be provided on a larger scale, there was a tendency for centralized generation systems and for developing the necessary transmission infrastructure to reach the, often quite remote from the generation sites, load consumption centers. Around the 1980s however, Governments in North America, introduced power deregulation policies and invited the commissioning of distributed generation via the PURPA and Energy Policy Act measures. Subsequent environmental and global warming concerns, along with the need to decentralize power generation in order to account for the availability of renewable resources, caused new DG-oriented technologies to mature [5] and have led, ever since, to continuously increasing DG penetration in the existing distribution systems.

Standards have been, and still are, developed to integrate small and medium size DGs, typically not exceeding the 10 MVA rated capacity, into the legacy electric power distribution systems. UL 1547 and IEEE 1647 are typical such standards. Standards Coordinating Committee (SCC) 21 has administrated the development of IEEE 1547 standards, that provide criteria and requirements for interconnections of different DGs with electric power systems (EPS) [5]. UL 1741 standards are developed for preserving the integrity of Inverters, Converters, Controllers, and Interconnection Equipment for use with Distributed Energy Resources [6].

1.2.1 Interconnection Protection Issues

There are many protection-related issues to be addressed before any DG is permitted to be connected to a distribution grid and, as already mentioned, they mainly relate to DG islanding and to area-EPS fault inception. DG islanding is safeguarded against by the DG islanding Interconnection Protection. This type of protection addresses the phenomenon of having one or more DGs still feeding part of the feeder when the main feeder connection to the power system has been severed. DG islanding raises important issues such as: a) personnel safety since still connected generating resources supply power to a supposedly disconnected feeder, b) equipment power quality supply concerns due to the resulting power imbalance within the formed island, and c) generation of unacceptable temporary system over voltages depending on DG interconnection transformer winding connections. The presence of high-speed reclosing can also impose severe timing constraints for DG islanding detection, in order to avoid out of phase reclosing conditions on islanded DGs.

In terms of Fault current protection, from the utility protection perspective integration of the Distributed Generation (DG) can lead, in the event of an area-EPS fault, to protection coordination loss [7–11], unintentional islanding [12, 13], over-voltages and ferroresonance problems [14, 15], defy fuse saving schemes [9], lower the magnitude of utility phase and ground contributions thus compromising the sensitivity of both phase and ground over current protection [16] and cause sympathetic tripping on non-faulted adjacent feders [7] while the possibility of ferroresonance surfaces in the presence of floating neutral DG interconnection transformers [1, 17, 18].The DG Fault Interconnection Protection however, that forms the objective of this thesis, addresses foremost the issue of preventing the distribution feeder infrastructure from being exposed to elevated fault currents originating from the DGs. This is the reason why standing DG Interconnection guidelines require immediate disconnection of DGs in the event of an area-EPS fault. It should be mentioned that there are cases that DGs should not be disconnected immediately under fault conditions but stay connected in order to provide voltage support by the time system faults are cleared. These Voltage Ride Trough (VRT) requirements, typically of concern to larger meshed systems, are not accounted for in this thesis since only pure distribution type generating resources are assumed.

Different technology vintage DGs exhibit different dynamics during faults. The worst type of DG fault current contribution-wise, is the synchronous DG since it is characterized by both sizeable and relatively prolonged fault contributions due to its inherent flux dynamics. The presence of voltage regulators can further exacerbate this unwanted characteristic. This eventuality, however, is not accounted for in this treatment since current practice precludes their use on the basis that any DG-exercised voltage control conflicts with utility-oriented feeder voltage control strategies. Inverter based DGs, on the contrary, typically limit the fault current to levels close to their rated operating current in order to avoid damaging the power electronics equipment.

1.2.2 Typical DG Fault Interconnection Protection Assembly

Generally, the phase and ground fault protection at the Interconnection Protection level are provided by instantaneous over-current (50), inverse time over current (51), directional (67), and distance (21) relay types [1, 15, 19]. This protection does not need any communication but might not be able to detect all the faults in the distribution network. So, the regulations may also require availability of a transfer trip switch. This is a dedicated communication channel that is used to trip the DG when a fault is detected in the distribution system. For interconnection that is grounded on the utility side, the over-current fault protection package assembly can be seen in Fig. 1.1. The overcurrent phase and ground protection is mainly provided by instantaneous (50 and 50N) and inverse time (51 and 51N) overcurrent relays. The directional (67 and 67N) and distance (21 and 21N) relays are also employed in the interconnection fault current protection, mainly to address faults on the low-voltage side of the DG transformer.

1.3 Power System Protection

In what follows, a brief overview of the main objectives of Power system protection is presented in order to put the DG Fault Interconnection Protection in that general context. Furthermore, various proposed methods and hardware dedicated to shunt fault detection are also reviewed.

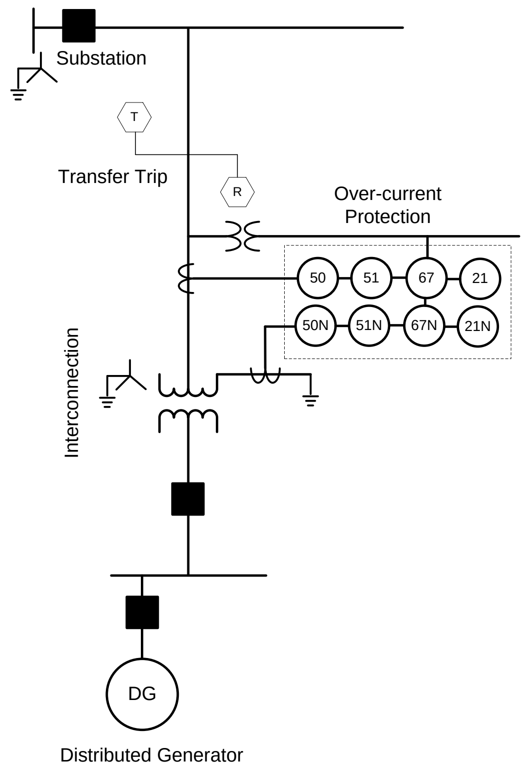

Fig. 1.1 Typical DG Interconnection Protection [1].

1.3.1 Power System Protection Requirements

Power system protection is one of the most important aspects of electrical power systems. Its objectives are to

- Ensure personnel safety
- Improve power system operations including system stability
- Protect the power system assets such as generators and transformers etc.

System protection, in general, is required to detect any abnormal conditions in the system and isolate the minimum number of devices in order to bring back the system to a normal operating condition as soon as possible. A lot of work has been done in the field of protection and many standards have been compiled e.g. IEEE Std 242-2001, the IEEE Buff

Book in the context of the present work. The IEEE Buff Book is a typical end-user standard (application guide) and describes techniques for the proper selection, application, and coordination of the protective devices for industrial plants and commercial buildings [20].There are many working groups such as CIGRE SC B5 responsible for developments in other Power Systems Protection areas of interest. Any type of protection needs to be selective, reliable, rapid whenever warranted, and adaptable to the changing system operating and/or topological conditions [21, 22], having the fundamental requirements outlined below.

Selectivity

IEV 448-11-06 defines selectivity as the ability of a protection system to identify the faulty section and/or phase(s) of a power system [23]. The impact of protection schemes on the resultant operation of the power system network should be minimal. For example if a fault occurs on one of the feeder laterals, the protection scheme should not cause outages at other healthy laterals.

Reliability

Reliability is the probability that the protection can perform its required function under given conditions and within a well-defined time interval. It consists of security and dependability indices [23]. Security is the probability of not having an unwanted operation under given conditions within the time interval of interest. In the present context, this means that the DG fault Interconnection Protection should not act when there is no fault in the area-EPS . Inadvertent protection operations can interrupt the power supply to the customers and impact the system stability. Dependability is defined as the probability for not having the intended protection scheme failing to operate, when needed, within the time interval of interest. In the present context, this means that the DG fault Interconnection Protection should act when there is an area-EPS fault. Failure to detect such faults can damage the power equipment or lead to complete collapse of the power system networks.

Speed

Any abnormal conditions developed within the power system need to be cleared as soon as possible to maintain the system stability and to prevent causing damage to the power system equipment. Again, in the present context, if the DG fault Interconnection Protection does not preclude the DG fault contributions from feeding the faults, damage can occur in the distribution system infrastructure.

Adaptability

Protection needs to be adaptable to the changing system conditions. For example under N-1 contingencies, the protection should be able to act properly, possibly under revised settings, so that system does not lose stability. These contingencies could pertain to either connected resources or changed system topology.

Backup Protection

Redundancy is another important protection requirement. When a protection equipment fails, there should be a backup to address the system anomaly, in the present context system faults. The backup can be either provided locally where a duplicate equipment is added at the same location or upstream if the local equipment fails to act.

In terms of DG Fault Interconnection Protection the coordination requirement can be of concern if there are reasons to have the DG protection be time-coordinated with the utility fault clearance protection, a concern not directly applied to this investigation that deals with fault detection alone.

Reliability requirements however must be fully enforced at the DG protection level since neither failing to detect a fault nor nuisance-trip a DG are acceptable, particularly at higher DG penetration levels.

In terms of speed the DG fault Interconnection Protection should comply with the standing guidelines and be: a) as sensitive , if not more, as the existing feeder protection, b) be able to detect a fault immediately upon its inception, thus the need to train the proposed IR on first-cycle fault current information.

The adaptability of the proposed IR follows the adaptability of the currently used protective devices and it will have to be retrained for another feeder/DG configuration pretty much as a phase/ground over-current relay needs to be reset under significant system topological changes.

1.3.2 Existing Protective Relays Devices

Different types of relays used in power systems protection are discussed in the following.

Traditional Overcurrent Relays

Electromechanical relays were introduced in the early 1900s. C.E.L. Brown was one of the pioneers to design and patent an a.c. overcurrent inverse-time limit relay in 1902 [24]. His relay had an aluminum disk driven by a shaded pole electromagnet under overcurrent conditions. Many improvements were made to the electro-mechanical relays but the fundamental principles of the design remained. The movement of armatures, be it plungers or discs, operated contacts that initiate protective action like tripping a circuit breaker in case of overcurrent conditions beyond specified thresholds. There are three types of electromechanical relays: Attraction relays, Plunger type relays, and Induction relays [22, 25]. Attraction and Induction relays are used for inverse time overcurrent protection while Plunger type relays are used to provide instantaneous protection. These relays are still used in practice because they are very robust and reliable. They are well understood and have longer life spans than the modern relays [26].

Solid State Relays

The solid state relays were introduced in 1960s. These relays are also called static relays because they have no moving parts. Solid state relays can perform all the traditional overcurrent relay functions. However, these relays use low-rating power components that cannot tolerate harsh weather conditions and they require an independent power supply [22]. They are not as simple as mechanical relays. So, they have not completely replaced the traditional relays.

Microprocessor Relays

The first microprocessors based relays were commercialized in 1979 [27]. However, they did not gain immediate recognition from the industry because they were considered to be neither reliable nor economical. Microprocessor relays continued to evolve and in the late 1980s multifunction relays were introduced. Microprocessor relays offer many advantages like [27]:

- **Multiple functions:** These relays can provide multiple setting groups, programmable logic, adaptable logic, sequence-of-events recording, and ability to communicate with other equipment

- **Reduced cost:** Microprocessor relays are less expensive than electromechanical and solid state relays
- **Custom logic schemes:** Users can program custom logic to provide more complex device tripping characteristics
- **Smaller panel space:** They take smaller space than other relay types
- **Sequence of events:** They have a memory that can store sequence of events occurred
- **Self-monitoring:** These relays can self monitor themselves and raise the alarm in case of abnormal conditions.

There are also shortcomings in applying microprocessor relays, namely:

- **Shorter life span**: The technology changes so fast that the relay technologies become obsolete very fast. The relay users need to ensure that all the relays are updated with new firmware.
- **Susceptibility to transients:** Unlike electromechanical relays, microprocessor relays are susceptible to harsh weather conditions and electrical transients. Microprocessor relays need to conform to the IEEE Std. C37.90 [28] for durability under harsh conditions.
- **Harder to commission:** With complex and continuously evolving technologies it is hard to commission the microprocessor relays.

Many different algorithms for programming digital relays are proposed in the literature and they are briefly reviewed next.

- **Frequency Analysis based Algorithms:** Fourier analysis transforms a time domain signal to frequency domain. Fourier analysis represents periodic functions by a set of discrete harmonic functions (sines and/or cosines) using the Equation 1.1 where $f(t)$ is a periodic function, Ω_0 is the fundamental frequency, n is the harmonic number of the frequency, F_n is the magnitude of the cosines at n^{th} frequency.

$$f(t) = \sum_n F_n e^{jn\omega_0 t} \tag{1.1}$$

Basic algorithms extract the fundamental frequency signal component to determine the fault current and voltages to either determine the impedance to the fault or differential current quantities. The Fast Fourier Transformation (FFT) is commonly applied to convert the signal from the time to the frequency domain [29, 30]. The same task of removing the dc component from the fault current can be accomplished using filtering, an approach adopted for the purposes of this investigation.

Since the frequency domain representation does not contain any time information, the Short Time Fourier Transform (STFT) was developed by Dennis Gabor to retain both. STFT uses a small time window and performs frequency analysis as the time window moves along the continuous signal. STFT has been used for fault classification in transmission lines [31]. However, STFT has a fixed window size and either good time and poor frequency resolution can be achieved by using a small window or poor time and good frequency resolution can be achieved using a larger time window. Wavelet transformations were subsequently developed to overcome the STFT drawbacks. In wavelet transformation, the signal is analyzed with different resolutions at different frequencies. A single wavelet function is contracted and/or expanded to achieve good time resolution at higher frequencies and/or good frequency resolution at low frequencies. Wavelet algorithms have also been successfully applied for detecting and/or locating faults [32, 33]. Modified time-frequency transformation algorithms have also been applied for detecting High Impedance Faults (HIFs) [34, 35].

- **Communication Technologies:** Communications have been successfully used in power systems protection to increase its reliability. They are provided using power line carriers, microwave, radio systems, satellite systems, and fiber optics. It is harder, however, to provide communication to electro-mechanical relays because they require sophisticated external wiring. With the advancements in digital relays, it has become much easier to embed communication. Communication protocols such as DNP 3.0 and IEC 61850 attempt to standardize the exchange of information between all Intelligent Electronic Devices (IEDs) [36, 37] allowing the potential implementation of centralized protection schemes and/or distribution automation functions. Southern

California Edison Company (SCE) has, for instance, built a high-speed wide area protection system that uses Centralized Remedial Action Scheme (C-RAS) [38]. They also demonstrated the use of remote controlled interrupters (RCI) and remote automatic reclosers (RAR) that communicate to isolate the faulty part of the distribution system thus minimizing the number of customers who will be affected from outages on the feeder [39]. Communication-assisted digital relays based on the synchronized phasor measurements have also been proposed for use in both the microgrids and distribution systems [40]. Despite many advances, the distribution protection remains largely non-communication based due to the relatively elevated cost of the required communication infrastructure.

- **Machine Learning:** Most of the digital relays machine learning algorithms are based on supervised learning such as Artificial Neural Networks (ANN) [41–48] and Data-Mining algorithms [49–53]. A set of training data that contains known inputs and outputs is provided to the algorithm. The algorithm processes the training data and provides a decision making model that can be used to predict the outputs for future unknown inputs. These models are generally used for solving complex non-linear problems, or problems of unknown mathematical structure, that are very hard to solve or cannot be solved analytically. Knowledge Based Expert Systems such as Fuzzy Logic algorithms are also found in the literature [54–56]. The system takes the inputs and based on a set of rules it provides output. These rules are typically determined by a human. Expert fuzzy logic systems aim to minimize the input required from experts to carry out complicated tasks.

  An Artificial Neural Network (ANN) attempts to mimic human brain decision making. An ANN consists of a large number of layer-structured neurons that are interconnected with each other by synapses [57]. These neurons take in a weighted input, apply non-linear functional analysis, and the resulting output is passed to the neurons in the next layer. The non-linear function is picked by the user and input weight factors are determined using back-propagation algorithms. A simple ANN structure can be seen in the Fig. 1.2. The inputs are passed to the neurons at the Input layer level. The number of neurons in the input layer is equal to the number of the inputs. The input neurons are connected to the hidden neurons through synapses. There can be many hidden layers despite the fact that Fig. 1.2 illustrates the concept showing only one. Finally, there is an output layer also linked to the hidden layers through synapses.

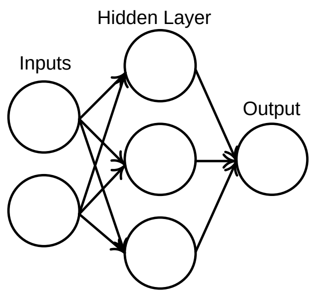

Fig. 1.2 Artificial Neural Network (ANN) Structure

Neural networks have been proposed for detecting faults in distribution networks [41, 46, 48], for classifying the transmission line fault types and for identifying the implicated faulted phases using voltage and current samples [47]. They have also been proposed for distance protection [42, 43], and for transformer protection as a means of distinguishing between inrush and internal fault currents in a transformer [44, 45].

Another machine learning based tool is the so called ”Fuzzy Logic” algorithms. A fuzzy logic system capitalizes on the available human knowledge in a specific domain of application and makes useful inferences based on it [57]. Fuzzy-logic systems have been applied to shunt fault detection [54], distance [55], and transformers protection [56]. However, fault detection methods need to be translated to fuzzy rules and expert knowledge is needed to come up with meaningful fuzzy rules.

Last but not least, data-mining is one of the currently popular machine learning tools. Data-mining is the analysis of observational data sets to find relationships and to summarize the data in ways that are both understandable and useful to the user. One of the classification methods of data-mining uses decision trees. Decision trees consist of decision nodes connected by branches that extend downward from the root node and terminate at leaf nodes [58]. Classification and Regression Trees (CART) and C4.5 are the most popular algorithms for constructing the decision trees. Data mining techniques have also been applied for faults and islanding detection [49, 50]. These techniques have been used in this thesis to set the proposed Intelligent Relay and are further explained in Chapter 3.

1.4 Thesis Objectives

1.4.1 Proposed Approach

The performance of data-mining based static relays based on Decision Trees is scrutinized here for DG Fault Interconnection Protection duty because by virtue of the resulting simple Decision Trees (DT) structure: a) The relay tripping logic and its thresholds are directly determined and b) The so obtained relay tripping logic and thresholds are directly interpretable. The fact that the so produced decision trees are derived on strictly local system information makes the proposed relay independent of any communication requirements. For the task at hand, data-mining is used to develop decision trees through processing of a representative set of events that might occur in a given distribution system. The CART based Matlab data-mining algorithm is used to train the decision trees. For each system event, various variables such as symmetrical RMS fault currents and fault voltages are measured at the DG interconnection utility side. First cycle data are used for fault detection purposes, for reasons already explained. Once the decision tree is determined during the so-called "classifier training stage", it needs to be tested for decision-making robustness. The key property of a decision tree used for setting relays is that it must be able to credibly identify both faulted and non faulted system events. Its performance, according to well established machine theory practices, is checked against a new set of events contained in a "testing set" that comprises system events different from the ones contained in the training set and quantified through the reliability performance metrics of

a) **Security Index**, for quantifying the probability of properly identifying non-fault system events, thus providing a direct indicator of DG nuisance tripping tendencies

b) **Dependability Index** for quantifying the probability of credibly recognizing system faults

1.4.2 Intelligent Relay Design Objectives and Testing

This thesis proposes an Intelligent Relay, set using Data Mining methods, to be used for area-EPS shunt fault detection as part of the DG Fault Interconnection Protection. More specifically:

- The first IR design requirements aim, primarily, at addressing the task of detecting all types of shunt faults of various severities, both symmetrical and asymmetrical, occurring anywhere within the considered distribution feeder.

- The second IR design requirement of the proposed IR is to provide credible fault recording information by properly identifying the shunt fault type and the implicated faulted phase(s).

- The above-stated IR functions are tested for one and multiple synchronous generators on the same distribution feeder for both Delta-Wye and Delta-Delta DG interconnection transformer connections. The performance of the proposed IR is tested both dependability and security wise for a large number of independent system events and its performance metrics are compared with the like performance of currently used protective devices.

- The applicability of the proposed relay is also tested in the Real Time Simulation environment using the OPAL-RT RTS as a Hardware in the Loop application (HIL) using an actual commercial relay incorporating the relay settings obtained through Data Mining methods.

1.5 Summary of Contents

This thesis contains the following chapters:

Chapter 2: Background and Modeling Description

This chapter reviews the basic aspects of the shunt faults modeling and the types of DG interconnection transformers to be used. The synchronous generator dynamic model, the over head distribution line models, network and DG transfomer models to be used are also discussed. The benchmark distribution feeder used contains no underground cable segments.

The chapter continues with the description of the medium voltage benchmark distribution systems, both single and multi-machine, on which the intelligent relays are trained and tested. The 25 kV distribution feeder is considered balanced, at this voltage level, in compliance with standing Interconnection guidelines that require minimal negative sequence voltage content at the DG connection points.

Next, the conventional protective devices to be used as an alternative means of Interconnection Protection for comparison purposes with the IR are reviewed, and their contemplated settings are outlined.

The definition of the common performance metrics used for all types of protective devices used in this work constitutes the last topic in this chapter.

Chapter 3: Data-Mining and Classification Decision Trees

This chapter addresses aspects of the general multi-disciplinary application aspects of data mining which is the process of uncovering previously unknown relational patterns in large volumes of data. The importance of classification tools in successfully discovering these hidden data patterns is then reviewed and the decision tree classifiers are introduced as the method of choice for the task at hand. The chapter concludes by applying these notions to the particular task of setting DG Interconnection Protection intelligent relays for fault detection duty.

Chapter 4: Fault Interconnection Protection using Intelligent Relays for a Single DG

The system events that train the Intelligent Relay are described in this chapter and the performance of the IR mounted on a single synchronous DG is illustrated for the tasks of: a) detecting LLL, LL, LLG, and SLG faults for Y-grounded and Delta utility side DG interconnection transformer connections, b) identifying the shunt fault type and the implicated faulted phases. It is noticed that the intelligent relay out-performs the conventional relay package and that it exhibits higher sensitivity for high resistance ground faults. The chapter is concluded with the block diagram of the proposed Intelligent relay that describes its functionality.

Chapter 5: Fault Interconnection Protection using Intelligent Relays for Multiple DGs

In this chapter, the notions and methodologies applied to the case of a single DG are extended to the case where three different ratings synchronous generators are connected at different locations of the test distribution feeder. The two additional synchronous generators are connected to the feeder using different interconnection transformer configurations.

Chapter 6: Hardware in Loop Application

The current and voltage waveform resulting from area-EPS faults simulated on the test distribution feeder with three synchronous DGs are ported into the OPAL-RT Real Time Simulator environment while the fault detection logic is implemented on a SEL 351 R commercial relay. Different fault and non-fault events are simulated in the real time simulator and the obtained results are also shown therein, thus illustrating the ability of an actual microprocessor relay to perform the intended functions in the Real Time simulation environment.

Chapter 7: Conclusions and Future Research

This chapter encapsulates the conclusions of this thesis, by summarizing the fault detection duty performance metrics and superior ground fault detection sensitivity of the IR as well as its ability to credibly perform recording functions. The chapter concludes with further potential applications/extensions of the developed methodology.

Chapter 2

Modeling and System Description

This chapter discusses models for shunt faults used in the context of this thesis , illustrates the DG transformer interconnection connections to be considered, and discusses the relevant models for the synchronous DG and feeder overhead lines as used in the undertaken system studies. It also discusses two benchmark distribution systems with single and multiple synchronous generators for which the intelligent interconnection protection is developed in this thesis. The protective devices reliability performance metrics are also defined for later use.

2.1 Fault Modeling

There can be many types of faults in a power system. This thesis considers only shunt type faults, namely Three-Phase (LLL), Single Line to Ground (SLG) , Line to Line (LL), and Double Line to Ground (LLG), implicating three (LLL), one (SLG), two system phases (LL, LLG) and ground whenever applicable. The above faults have been considered as both arcing and solid, with a maximum arcing resistance of 3 Ohms for faults not involving ground (LLL and LL) and up to 45 Ohms to account for ground resistance for faults involving ground (SLG and LLG).

2.1.1 LLL Faults

LLL (A-B-C) faults occur when all three phase conductors come inadvertently in contact with each other. They are very rare in nature but they may yield the highest magnitude prospective fault currents when far from generating stations. In practice, the fault is never solid thus the model depicted in Fig 2.1 illustrating the arcing resistances Rf that is assumed to be equal for all phases. The arcing resistance typically ranges from 0 Ω to 2 Ω [59]. The existence of ground resistance is not considered here in view of the fact that all three phase arcing resistances are assumed equal.

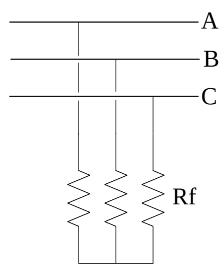

Fig. 2.1 LLL Fault Model

The typical LLL fault currents and system voltage phasor diagram can be seen in the Fig. 2.2. The LLL faults are symmetrical in nature. High currents flow through all three phases and are of equal magnitudes. The fault voltage phasor magnitudes are depressed depending on the fault location from the source but the magnitudes on all three phases are the same for balanced systems, as is the case considered here. The phase currents lag from the voltages by an angle θ that depends on the X/R ratio between the source and the fault location. For all practical purposes, fault currents are are highly inductive at least for the overhead distribution circuitry, assumed here.

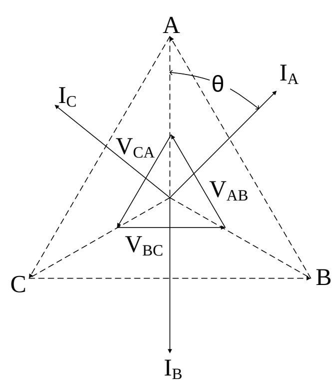

Fig. 2.2 LLL Fault Phasors [2]

2.1.2 LL Faults

LL (A-B, A-C, or B-C) faults occur when only two of the system phases come in contact with each other. The considered LL (B-C) fault can be seen in the Fig. 2.3. The phases B and C are in contact with each other through an arc resistance of $2R_f$.

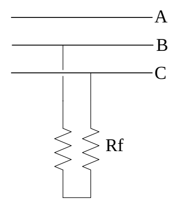

Fig. 2.3 LL Fault Model

Fig. 2.4 shows the LL (B-C) fault current and voltage phasors. The line to line voltage phasor V_{BC} reduces and the current phasors I_B and I_C increase in magnitude.

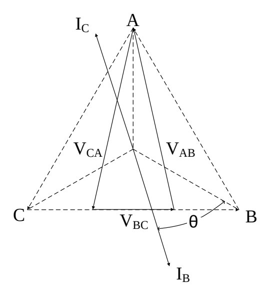

Fig. 2.4 LL Fault Phasors [2]

2.1.3 LLG Faults

LLG (A-B-G, A-C-G, or B-C-G) faults occur when two of the phases come in contact with each other and the ground. The considered LLG fault model (B-C-G) can be seen in the Fig. 2.5. The phases B and C are in contact with each through an arc resistance of $2R_f$ and in contact with ground with a resistance of R_g.

Fig. 2.6 shows the LLG (B-C) fault current and voltage phasors. The line to line voltage phasor V_{BC} reduces and the current phasors I_B and I_C increase in magnitude.

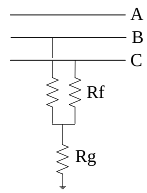

Fig. 2.5 LLG Fault Model

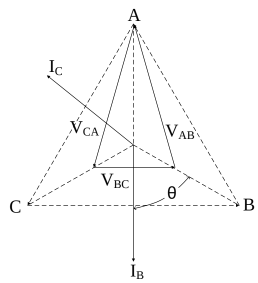

Fig. 2.6 LLG Fault Phasors [2]

2.1.4 SLG Faults

Single Line to Ground (A-G, B-G, or C-G) faults occur when a system phase comes in contact with the ground. SLG faults are the most common faults, barring the fact that actual distribution systems contain many single-phase lateral arteries. The considered SLG fault model can be seen in the Fig. 2.7. The phase A is grounded with a ground resistance of R_f.

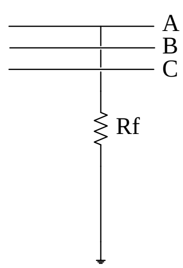

Fig. 2.7 SLG Fault Model

Fig. 2.8 shows the SLG (A-G) fault current and voltage phasors. The phase A voltage is depressed leading to a high fault current in the same phase.

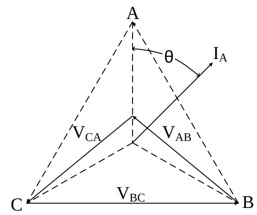

Fig. 2.8 SLG Fault Phasors [2]

2.2 DG Interconnection Transformer Modeling

The three phase DG interconnection transformer may feature different winding configurations like Delta-GrdY and GrdY-GrdY etc. The studies in this thesis consider both types of interconnection transformers, since they influence quite differently the fault current contributions from the DG and the system post-fault performance in general.

2.2.1 Delta-Grounded Y Interconnection

Delta-Y Grounded interconnection configuration is shown in Fig. 2.9. The transformer is un-grounded (Delta) on the DG side and solidly grounded on the utility side. This configuration provides a ground fault current contribution when a ground fault occurs in the distribution system, while, potential dynamic overvoltages are minimized.

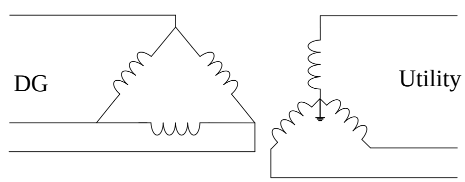

Fig. 2.9 Delta-GrdY Interconnection

2.2.2 Delta-Delta Interconnection

The alternative Delta-Delta DG transformer interconnection can be seen in Fig. 2.10. Both the DG and the utility side are ungrounded in this case. This transformer configuration offers no residual ground fault currents and area EPS faults may be the cause of sizable dynamic overvoltages.

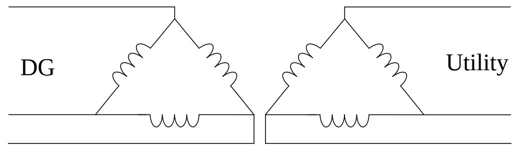

Fig. 2.10 Delta-Delta Interconnection

2.3 Synchronous Generator Modeling

The synchronous generator is a rotating AC machine widely used for power generation. It is a well understood and widely used DG technology used to directly connect distributed generating resources in AC distribution systems without overdue concerns about power quality issues. It retains its popularity despite the widely available recently well developed alternative Voltage Source Inverter connected DG technologies. The synchronous generator, in its classical configuration, has a stator and a rotor made of magnetic steel. The stator carries an armature winding that, in normal steady state operation, generates symmetrical three phase voltages and load currents to the system. The rotor is, typically, supplied with a direct current to produce a magnetic flux. The rotating rotor magnetic flux induces an electromotive force (emf) in each phase of the armature winding that is the source of supply of AC current to the power system under a controllable power factor [60].

Synchronous generator models can be complex and diverse depending on the application at hand and/or the phenomena studied. They can assume a wide range of complexity ranging from a simple voltage source behind a time-varying impedance to complex sixth order dynamic models based on differential equations. For the purpose of this thesis a full sixth-order dynamic synchronous generator model is used [61] in order to properly capture the flux dynamics under fault conditions. It has, however been found that the model used yields consistent results, symmetrical fault currents-wise, with the standard IEEE-recommended model of the constant internal voltage behind a sub-transient impedance. The reason the full order model fault currents were compared against the sub-transient simplified model fault is because the intelligent relays are to be trained using first-cycle symmetrical DG contributions for fault detection purposes at the DG Interconnection protection level.

2.4 Distribution Feeder Line Modeling

The distribution overhead lines are modeled using the standard medium length three phase PI section. The line has series inductive and resistive elements that are assumed equal on all three phases. Mutual inductive coupling is also assumed present between the three-phases under the assumption that the resulting impedance matrix is cyclic, i.e. the mutual inductive coupling is the same for any two of the three system phases. At the two ends of the line there are shunt capacitors that are also considered to be the same for all three phases, despite the fact that their value is small due to the non-significant line lengths of the considered overhead benchmark feeder. It is reminded that no underground cables were considered as part of the distribution infrastructure.

2.5 Single DG Distribution Feeder

A typical rural distribution feeder is used for building the decision trees. The feeder has about 11 MW of system load and has nominal line to line voltage of 25 kV and the total system load has a power factor of 0.98. There is a synchronous distributed generator (DG) in the feeder that supplies 30% of the system load.

The feeder was reduced to a balanced three phase system [62]. The reason the test distribution feeders were considered, throughout this work, to be balanced is to comply with standing Interconnection guidelines requiring a minimum content of negative sequence voltage at the DG connection points. The main three phase feeder trunk was retained and the unbalanced loads were converted to equivalent balanced three phase spot loads. The reduced feeder model can be seen in the Fig 2.11. The feeder loads, lines, and the detailed component variables are provided in the Appendix A.

The substation has a short circuit level of 1000 MVA and is represented by its thevenin equivalent. It feeds the 25 kV four-wire, multi-grounded distribution system through a 114.3 kV/24.94 kV Delta-Yg main transformer. The 25 kV distribution system has a nominal total demand of 11.064 MW and 2.345 MVAr. The distribution main feeder X/R ratio ranges from 3.4 near the main substation down to 0.830 at the feeder end-points. The laterals X/R ratio range from 0.59 to 1.35.

A 5 MVA synchronous generator supplies 30 % of the system load in addition to its auxiliary load of 250 kW. The DG operates in power factor control mode and maintains a

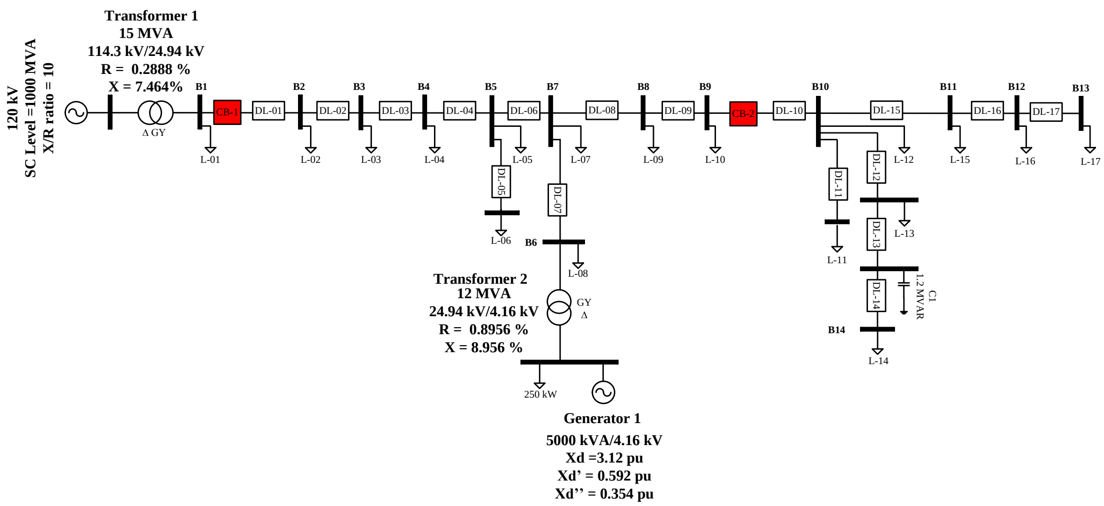

Fig. 2.11 Reduced Single DG Feeder Model

0.95 lagging power factor at the PCC. It is connected to the distribution system through a 25 kV/4.16 kV interconnection transformer. Two different winding configurations are considered, namely Delta-Yg and Delta-Delta

In terms of prefault loading conditions, Table 2.1 indicates the DG load currents under different nominal feeder loading conditions, i.e. ranging from 20% to 100% feeder loads, with DG quantities referred to the utility side of the DG interconnection transformer. It is seen that there is, indeed, a marked difference in the DG load current, assuming that the DG supplies 30 % of the feeder load on all counts. These differences however are insignificant when compared to the ensuing fault current magnitudes, a fact consistent with the considered voltage level of the feeder. In any case, intelligent relays were trained for 100 % feeder load but testing comprised all three loading feeder states for completeness.

2.6 Multiple DG Distribution Test Feeder

The distribution system with three DGs can be seen in Fig. 2.12. It is the same feeder with two additional synchronous generators connected. Generator A has the same variables as before and supplies 30 % of the system load. Generator B and Generator C have a

System Loading		Substation Measurements		DG Measurements	
%age	(MVA)	V (kV)	I (A)	V (kV)	I (A)
20%	2.26	26.17	35.17	26.10	18.63
60%	6.79	26.08	111.60	25.70	47.81
100%	11.31	25.94	180.12	25.24	77.74

Table 2.1 System Normal Conditions Voltage and Currents

capacity of 3 MVA and 4.5 MVA respectively and supply a 500 kVA and 580 kVA at 0.98 power factor. Gen A is studied with Delta-Yg and Delta-Delta interconnections, while the DG transformer connections of GEN-B and GEN-C are taken to be Delta-Yg through an impedance of j20 Ohms (utility side) and Delta-Delta (utility side) respectively .

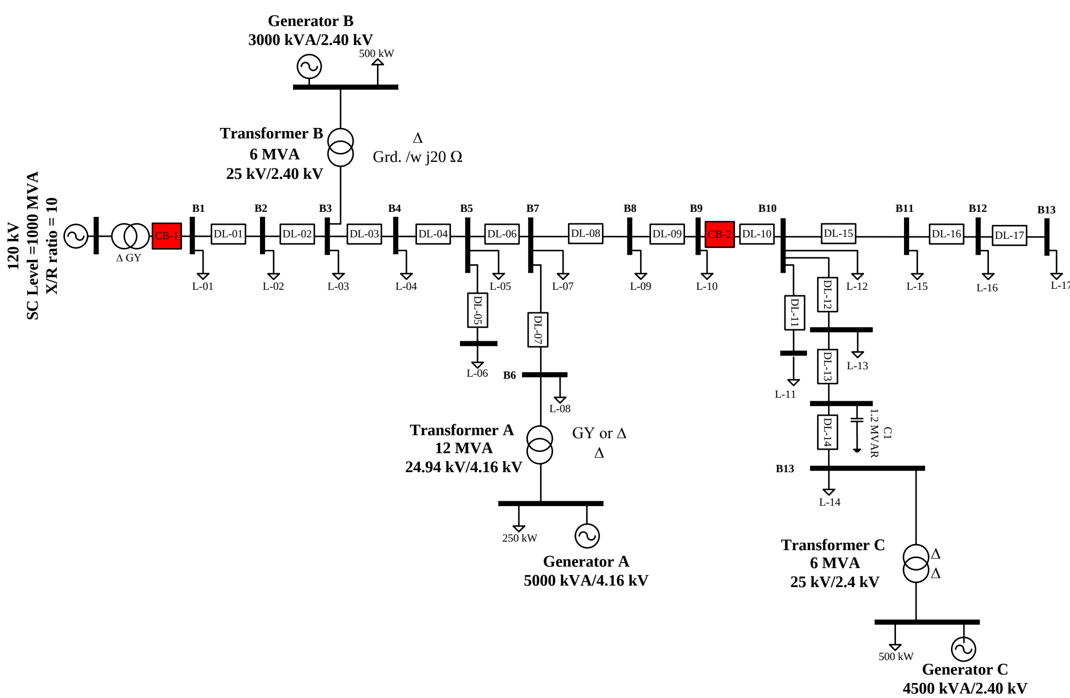

Fig. 2.12 Multiple DG Distribution System.

Table 2.2 shows the steady state load currents for all three DGs under the above-stipulated loading conditions. It is seen that, again, there is a marked difference in the

DG-A load current across the varying feeder load levels. The remaining two DG load currents do not vary significantly, as expected. All DG load currents are, nevertheless, still well below fault current magnitudes. Following the practice of the single-DG systems, intelligent relays for all DGs were trained for 100 % feeder load and tested for all three feeder loading conditions.

System Loading		Substation Measurements		DG A Measurements		DG B Measurements		DG C Measurements	
%age	(MVA)	V (kV)	I (A)	V (kV)	I (A)	V (kV)	I (A)	V (kV)	I (A)
20%	2.26	26.50	43.02	27.22	12.98	27.40	29.38	26.70	37.46
60%	6.79	26.36	57.47	26.60	43.67	26.51	31.20	26.39	38.18
100%	11.31	26.20	118.80	25.86	75.60	25.61	33.15	26.05	38.99

Table 2.2 System Normal Conditions Voltage and Currents

2.7 Currently used protective devices

Phase, ground, and voltage-restraint relays are considered here as representative conventional protective devices. Their functions, ANSI-number designation and assumed settings are described below. These devices under the considered settings are the ones whose performance is later compared to the performance of the intelligent relay using common performance metrics.

2.7.1 Phase Relay Protection - 50

The signature of shunt faults is the development of elevated phase currents. Instantaneous relay (50) pick up threshold settings are selected so that the relay trips without any intentional time delay once the sensed current exceeds that threshold. Depending on the application, instantaneous over-current relays may have threshold settings ranging from four to ten times the prospective peak load current [59]. For the studies at hand, the instantaneous over-current relay thresholds have been set, in the interest of avoiding undue insensitivity, at twice the prospective DG load currents, per Tables 2.1 and Table 2.2 above.

2.7.2 Ground Relay Protection - 50G

Ground faults like SLG and LLG introduce zero sequence (residual) ground fault currents to multigrounded distribution feeders as is the case examined here. Given that the distribution feeder is considered balanced, no load unbalance considerations apply here in selecting the pick-up thresholds of these devices. They are set to two times the DG full load current.

2.7.3 Voltage Restraint Relay - 50V

The voltage restraint relay (50V) adjusts its pick up current threshold as a function of the voltage it senses. Its pick up current is set here to two times the steady state current at the nominal system voltage. This is multiplied by the voltage deviation ratio as shown in Eq. (2.1):

$$I_{pick\ up} = 2 * Steady\ State\ Current * \frac{Actual\ Voltage}{Steady\ State\ Voltage} \tag{2.1}$$

2.7.4 Protective Devices Performance Metrics

The reliability performance metrics of all protective devices, including the Intelligent Relay, are quantified in terms of dependability and security and are calculated as ”success rates” in recognizing particular types of system events as explained below.

Dependability Index

The Dependability index refers to the ability of the relay to detect a shunt fault and is quantified as the percentage of actual fault events detected within a given testing set. It is mathematically defined by Eq. (2.2):

$$DI = \frac{DFE}{NFE} \tag{2.2}$$

where, DFE is the Number of Detected Fault Events, NFE is the Total Number of Fault Events, within the considered testing set.

Security Index

The security index relates to the ability of the protective devices to avoid nuisance tripping. In the present context, the protective device should not operate for a system event that is not a shunt fault. The security index is defined by Eq. (2.3):

$$SI = \frac{DNFE}{NNFE} \tag{2.3}$$

where, DNFE is the Number of Detected Non-Fault Events, NNFE is the Total Number of Non-Fault Events, within the considered testing set.

2.8 Conclusions

This chapter summarizes the models of the distributions feeder, the distributed generator and the associated three-phase transformer connections that are to be used in this work. The conventional protective devices functions and settings that are to be compared performance-wise with the Intelligent relays are also given, along with universal performance metrics that are to be applied to all considered relays. The performance metrics defined are used to analyze the applicability of data mining techniques used for setting intelligent relays destined to perform fault detection at the DG intertie protection level.

Chapter 3

Data-Mining and Classification Decision Trees

This chapter addresses aspects of the general multi-disciplinary application of data mining which is the process of uncovering previously unknown relational patterns in large volumes of data. The importance of classification tools in successfully discovering these hidden data patterns is then reviewed and the decision tree classifiers are introduced as the method of choice for the task at hand. The chapter concludes by applying these notions to the particular task of setting DG interconnection protection intelligent relays for DG fault interconnection protection detection duty.

3.1 Introduction

There are many different definitions of data mining, one being the process of finding useful correlations, patterns, and trends in large amounts of data using pattern recognition technologies and/or statistical mathematical methods [58]. Any application of data mining methods requires to [3]:

- Understand the application domain and the objectives
- Select the data set on which data-mining will be performed
- Choose the appropriate data-mining task: classification, regression, clustering, or summarization

- Apply the proper data-mining algorithm
- Evaluate and interpret the patterns recognized
- Deploy and test

There are many different data-mining methods broadly categorized as verification and discovery methods, summarized in Fig. 3.1. Conventional statistical methods such as goodness-of-fit test, t-test, or analysis of variance, used for evaluating proposed hypotheses, belong to the verification branch. On the other hand, discovery methods identify the underlying patterns in large sets of data. The discovery methods are further divided into description and prediction techniques [3]. Description methods such as clustering or visualization aim to understand the way data is structured, while prediction methods are used to construct a behavioral model to be successfully applied to new unknown samples. Predicting the behavior of unknown samples is typically made through comparing numerical values of certain variables characterizing the samples. These comparison mechanisms are called classifiers and, once designed based on previous knowledge, they can be used for future prediction.

In the present context, the intelligent relay sought to be set for fault detection can assume the form of a classifier that will recognize future shunt system faults versus future non-faulted events.

3.2 Classifiers and Decision Trees

The classifiers accommodating prediction methods can assume many forms of diverse mathematical complexity. Their very nature depends upon the application and their complexity on the complexity of the classification task. For simple classification problems containing only a small number of classes Decision Trees are a popular choice because:

- They are non-parametric meaning that no prior knowledge is required for the samples to be classified as to their probability distribution membership
- They assume a relatively simple and directly interpretable structure

Decision Trees partition data using a "divide and conquer" strategy on important attributes of the data to be classified by making a successive number of decisions at different

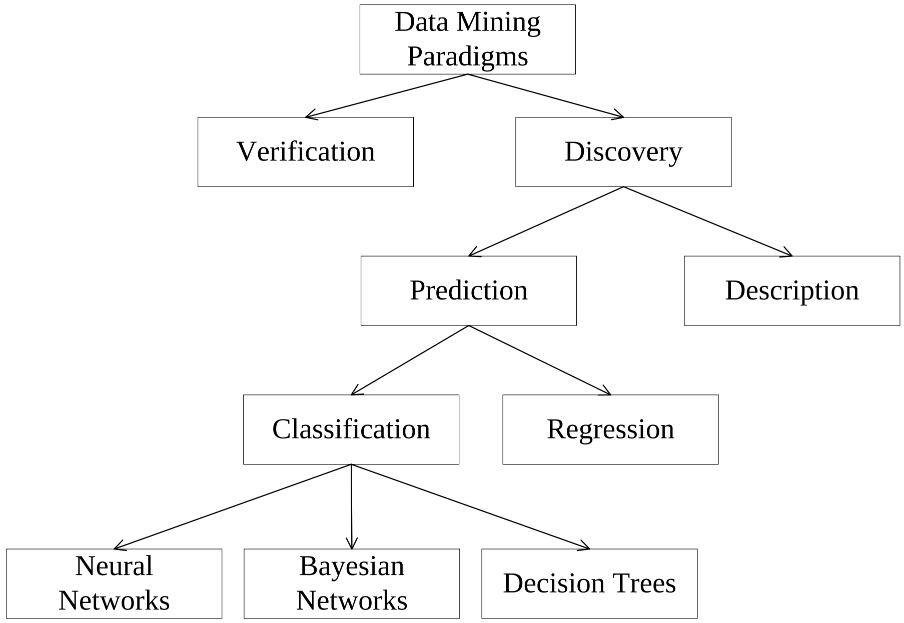

Fig. 3.1 Different Data-mining Methods [3]

consecutive levels. Every decision making juncture is called a decision node. The first nodes are known as "root nodes" while the last are termed "leaf nodes". A simple decision tree can be seen in the illustrative Figure3.2 that "decides" which car may be purchased based on income criteria which is, incidentally, the only decision variable entering the decision-making process.

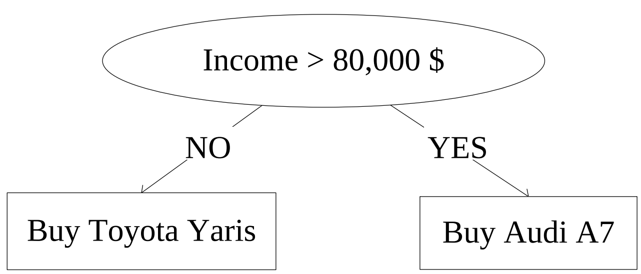

Fig. 3.2 A Typical Decision Tree

3.2.1 Growing Decision Trees

Decision trees are constructed using induction algorithms called decision tree inducers. These inducers find optimal decision tree structures by minimizing the resulting classification error, the number of the tree nodes, and/or the average depth of the tree. There are many top-down decision tree inducers like ID3, C4.5, and CART. ID3 and C4.5 growing the tree in a forward manner. The CART algorithm selected here, however, performs growing as well as backwards pruning [3]. These algorithms construct the decision trees in a top-down divide and conquer method using a set of data which contains samples of already known classification, called the training set. The training set is partitioned using the most appropriate discrete input attribute according to a node-splitting criterion, and a first data partition is effected creating a tree node. Each node is further subdivided into smaller subsets, using the same splitting algorithm, until a stopping criterion is met and/or the tree terminates with the leaf nodes containing samples that need no further classification. The process of building a decision tree classifier from a set of data with already known classification is called the classifier training stage. Clearly, the number and type of training samples will bear a direct impact on the future performance of the classifier because the training process can only capture the intelligence contained in the training set. The mechanisms used to make classification decisions at any node are called node-splitting criteria and they are briefly reviewed next.

3.2.2 Node Splitting Criteria

The decision tree node splitting can either be univariate or multivariate. In the univariate approach the decision tree inducers use only one attribute to partition the data at every iteration. In the more complicated multivariate node split approach, the data is partitioned using two or more attributes e.g. $x1 + x2 > 4$. Most of the decision tree inducers use univariate discrete splitting functions because they are simple to use and can solve most of the application problems. The approach of generating univariate decision trees has been adopted for the purposes of this work as well. Impurity based Criteria, Information Gain, Gini Index, Twoing Criterion are some of the most common univariate node splitting criteria [3].

3.2.3 Decision Tree Pruning

When tight stopping criteria are used, the decision trees underfit the data while loose stopping criteria generate large decision trees that overfit the data. To avoid constructing either underfitted or overfitted decision trees, pruning is employed. At first, loose stopping criteria are used that generate, ostensibly, a large rather overfitted decision tree. This decision tree is then reduced to a smaller tree by removing branches that do not contribute much to misclassification error. Reduced Error Pruning, Minimum Error Pruning (MEP), and Error Based Pruning (EBP) are some of the common pruning techniques mentioned in machine learning theory for decision tree inducers [3].

3.3 CART Algorithm

CART (Classification and Regression Trees) is one of the most popular algorithms for building decision trees [4, 58, 63–65]. It constructs decision trees in a top-down recursive manner. It goes through all possible splitting values for each attribute using an impurity based criterion called the Gini Index. The Gini Index is defined for a node, t, using:

$$Gini(t) = 1 - \sum_{i=1}^{k} p[(i|t)]^2 \tag{3.1}$$

where, k is the number of branches or classes from node t. $p(i|t)$ is the fraction of records belonging to class i. The Gini Index is a minimum, zero, when all the records belong to only one class. It is maximum when all the records are equally split among k classes. CART algorithm determines the "goodness" of split using:

$$\phi = Gini(parent) - \sum_{j=1}^{k} \frac{N(v_j)}{N} Gini(v_j) \tag{3.2}$$

where $Gini(parent)$ is the impurity measure of the parent node and $Gini(v_j)$ is the impurity measure of the child node v_j. $N(v_j)$ is the number of the records in the child node, v_j and N is the number of the records in the parent node. This can be explained using a simple example provided in Fig. 3.3.

Consider, as an example, a parent node that has 6 records from class C0 and 6 records from the class C1. The Gini Index of the parent node is $1-(6/12)^2-(6/12)^2 = 0.5$. Suppose

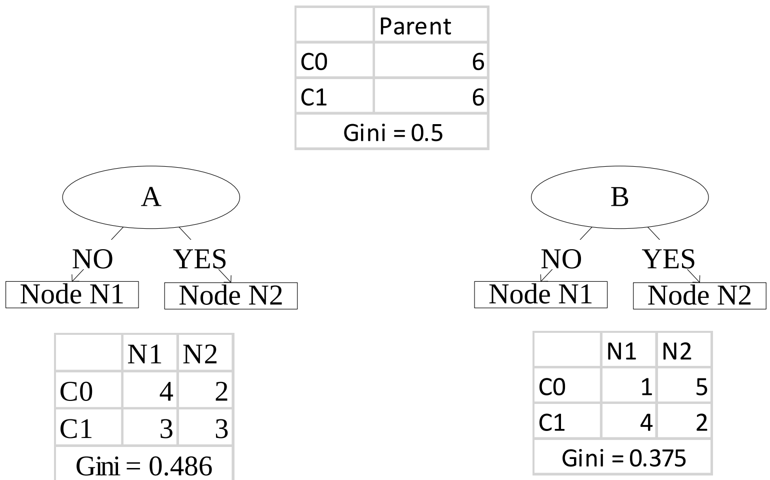

Fig. 3.3 CART Split Criteria [4]

there are two ways to split the data using either attribute A or attribute B. For attribute A split, the Gini Index of its children nodes N1 and N2 is 0.4898 and 0.480 respectively. The goodness of split, ϕ using attribute A, that has two nodes N1 and N2 containing 7 and 5 elements respectively in Fig. 3.3, can be calculated as $0.5-(7/12)*0.4898-(5/12)*0.480 = 0.014$. Similarly, the goodness of split for attribute B can be calculated as 0.125. The attribute B split offers better goodness than A, so it is preferred. The algorithm continues to split until a stopping criterion is met.

3.4 Application of Data-Mining to Interconnection Fault Detection

- **Preparing the Data:** In this thesis, the first cycle time domain phase currents are measured at the high voltage side (utility side) of the DG interconnection for different events simulated. During the pre-processing stage, the high frequency contents are removed using a low pass filter. Next, full cycle Fourier analysis algorithms are applied to extract the phase RMS currents and voltages at 60 Hz. The sequence variables are calculated using the Fortescue transformation where $\alpha = 120°$:

$$\begin{pmatrix} I0 \\ I1 \\ I2 \end{pmatrix} = \frac{1}{3} \begin{pmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{pmatrix} \begin{pmatrix} I_A \\ I_B \\ I_C \end{pmatrix} \tag{3.3}$$

The data-mining algorithm is applied to the first cycle from the fault inception events on the variables defined using x_1, x_2, ... x_n. The list of variables used can be seen in the Table 3.1.

Variables	Description
$x_{1,2,3} = I_A,\ I_B,\ I_C$	Magnitudes of phase A, B and C symmetrical RMS fault currents
$x_{4,5,6} = I_1,\ I_2,\ I_0$	Magnitudes of the positive, negative and zero sequence symmetrical RMS fault currents
$x_{7,8,9} = I_{An},\ I_{Bn},\ I_{Cn}$ where e.g. $I_{An} = \frac{I_A}{I_A+I_B+I_C}$	Magnitudes of normalized phase A, B and C symmetrical RMS fault currents
$x_{10,11,12} = V_A,\ V_B,\ V_C$	Magnitudes of phase A, B and C symmetrical RMS fault voltages
$x_{13,14,15} = V_1,\ V_2,\ V_0$	Magnitudes of the positive, negative and zero sequence symmetrical RMS fault voltages
$x_{16,17,18} = V_{An},\ V_{Bn},\ V_{Cn}$ where e.g. $V_{An} = \frac{V_A}{V_A+V_B+V_C}$	Magnitudes of normalized phase A, B and C symmetrical RMS fault voltages at the DG terminals

Table 3.1 Variables used in the Data-mining Process

The training data data sets is formalized as:

$$X = \begin{pmatrix} x_{1,1}(t_k),\ x_{2,1}(t_k),\ \ldots, x_{n,1}(t_k) \\ \ldots \\ x_{1,N}(t_k),\ x_{2,N}(t_k),\ \ldots, x_{n,N}(t_k) \end{pmatrix} \quad Y = \begin{pmatrix} Y_1 \\ \ldots \\ Y_N \end{pmatrix} \tag{3.4}$$

where:

X represents a matrix containing as row vectors, the vectors comprising all the variables defined in Table 3.1, with each row representing a training system event.

Y is the classification vector for each event within the training set. Its entries can assume only two discrete values in the present context, i.e. 1 for system events involving a shunt fault and 0 for a system event that contains no fault.

- **Application of Classification Tree Inducer:**

  The decision tree inducer is invoked during the training stage and produces a decision tree that classifies the above known system events, according to the numerical values of the variables (ranges) contained in the row vectors of matrix X, in two distinct classes, i.e in a class containing the events with shunt faults and in events containing no-system faults.

  The resultant classifier is therefore a two-class classifier and the decision tree produced will use exclusively variables that are directly, by definition, related to DG fault currents and voltages.

  The very structure of the decision tree classifier, by virtue of the variables and their ranges contained therein can be used as the fault detection Intelligent relay logic because the former will constitute the intelligent relay handles and the latter its thresholds.

  The CART based Matlab data-mining algorithm is used to accomplish the task [66].

- **Evaluating and Interpreting Obtained Decision Trees:** The quality of the obtained decision trees for future unknown system events, not contained in the training set, is evaluated using a set of testing events not used during the training stage, by calculating the already defined Dependability and Security indices. The same methodology is used to train and test the intelligent relay for recording duty.

3.5 Conclusions

This chapter revises the philosophy and the techniques of the data mining methodology as applied to fault detection and fault type identification duty for distributed generation fault interconnection protection.

Chapter 4

Fault Interconnection Protection using Intelligent Relays for a Single DG

This chapter applies the notions introduced in Chapter 3 to, actually, set the intelligent relays for shunt fault detection and recording duty for a single DG using the test-bench distribution system described in Chapter 2. The set of training system events used to construct the decision tree classifiers are described in detail and so are the contents of the testing set used to assess the protective devices performance. The performance of the Intelligent relays is also compared with the like performance of conventional relays, whose characteristics are also described in Chapter 2.

4.1 Distribution Test Feeder

The Single Line diagram of the feeder already described in Chapter 2 is reproduced here for the sole purpose of reference convenience. For further details in terms of data and variables, the reader is referred to Chapter 2.

4.2 Intelligent Relay Decision Tree Classifiers

The term "Intelligent Relay DT classifier" is, as already explained in Chapter 3, synonymous to the term "Intelligent Relay Tripping Logic", since the resulting DT classifier

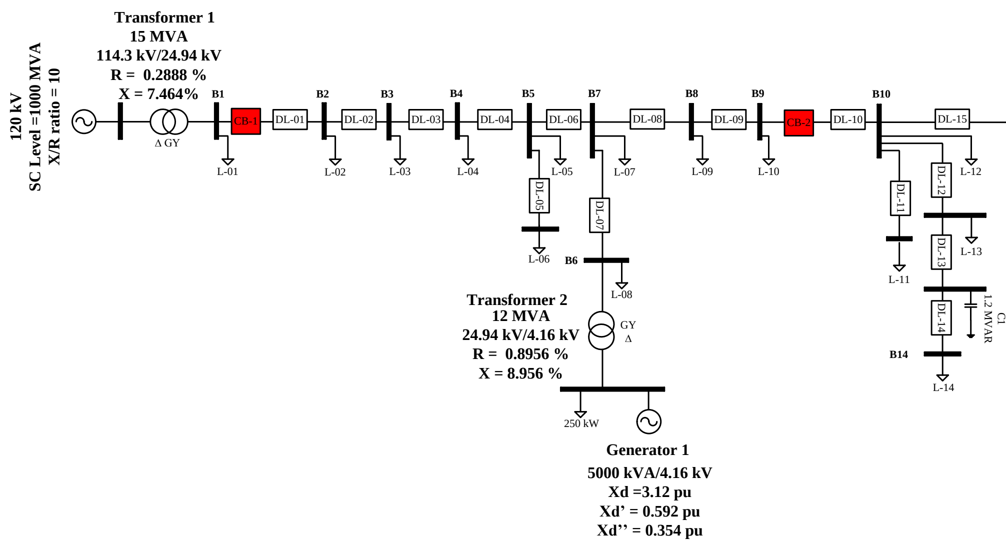

Fig. 4.1 Single DG Reduced Feeder Model

encapsulates, by construction, the complete relay functionality.

Two sets of Decision Tree (DT) classifiers are thus designed for the DG fault interconnection protection intelligent relays. The first relates to the duty of shunt fault detection and the second to satisfy the relay recording needs, meaning that there is one decision making logic for shunt fault detection and another decision making logic for addressing fault recording needs.

The former set of DTs classifier(s) is designed having in mind that the relay should detect a shunt fault, irrespective of type, occurring within the feeder, given that the interconnection guidelines simply require DG tripping under any fault condition.

The second set of DT classifier(s) need to further identify, once a shunt fault has been detected, the type of shunt fault and then, the faulted phases implicated in that particular fault condition.

Based on the above specification requirements it becomes clear that the first task the relay has to successfully carry out, hierarchy-wise, is fault detection. Once a shunt fault, any fault, has been detected, the next in line hierarchical task is to identify the shunt fault type. The third, and last, serial task the intelligent relay has to accomplish is to identify the system phase(s) implicated in the particular, just identified, fault type.

4.2.1 Training Set for Fault Detection Duty

Table 4.1 contains the system events that are used to build the DT classifiers (IR tripping logic) for shunt fault detection. These events are simulated for both Y-grounded and Delta utility-side DG interconnection transformer winding connections.

Events	Description
Non-fault (31 events)	Normal steady state operation
	Connection of one or group of loads
	Disconnection of one or group of loads
	Circuit breakers inadvertent
LLL - ABC (30 events)	$R_{arc} = 0, 2\ \Omega$
LL - BC (30 events)	$R_{arc} = 0, 2\ \Omega$
LLG - BCG (30 events)	$R_{arc} = 0, 2\ \Omega$ with $R_g = 0\ \Omega$
SLG - AG (30 events)	$R_g = 0, 20\ \Omega$

Table 4.1 List of Training Events

All these events are simulated at 100 % system loading (see also Chapter 2). Different non-fault events are also considered as training system events, comprising connecting or disconnecting bulk-loads and circuit breakers inadvertent operation for the sake of proper security assessment performance. In an effort to comply with the fundamental design requirement of detecting shunt faults anywhere within the distribution feeder, fault events are simulated at different locations along the test-bench distribution feeder (Fig. 4.1). System faults are simulated for the purposes of fault detection duty, as standard faults, i.e LLL faults comprising phases ABC, SLG faults on phased A and LL/LLG faults involving phases BC. Given that arc resistances greater than 2 Ω are not common [59], LLL LL and LLG faults are considered as having an arc resistance of 2 Ω. SLG faults, however, are simulated with ground resistance of 20 Ω. Given that common ground fault resistance values have been mentioned to be 1, 2, 20, 30, and 40 Ω a decision had to be made on selecting a representative value. Rural Electrification Administration (REA) standards recommend 40 Ω, in an attempt to attain considerable residual current sensitivity. This, however, was deemed overly conservative for the test distribution feeder in question and a compromise value of 20 Ω was selected for classifier training purposes. During testing, however, higher ground fault resistances were also accounted for.

4.2.2 Training Set for Shunt-Fault Type Identification

The fault type identification duty training set is a subset of the training set portrayed in Table 4.1. More specifically, the training set for designing DT classifiers aiming at identifying the shunt fault type, contain only the system events that included shunt faults. All system events not including faults are excluded.

4.2.3 Training Set for Faulted Phase Recognition

The training set used to design the DT classifiers capable of identifying the faulted phases is the training set used for shunt fault type identification, albeit augmented with faults covering all phase combinations. In other words, training events of the SLG-type are now added to the training set to address SLG faults on phases B and C. Similarly, LL and LLG faults now include the same system events used for phases BC but also for phases AB and AC.

4.3 The DT Classifier Testing Set

The DT classifiers obtained through the training procedure using the above described training sets, are tested on a new set of system events comprising both non-fault and fault events. All the testing set system events are different from the ones used in the training sets. And they are described, qualitatively, in Table 4.2.

Events	Description
Non-fault (57 events)	Normal steady state operation
	Connection of one or group loads
	Disconnection of one or group loads
	Circuit breakers inadvertent
LLL - ABC (243 events)	$R_{arc} = 0\ to\ 3\ \Omega$
LL - AC, BC, CA (375 events)	$R_{arc} = 0\ to\ 3\ \Omega$
LLG - ACG, BCG, CAG (375 events)	$R_{arc} = 0\ to\ 3\ \Omega$ and $R_g = 0\ \Omega$
SLG - AG, BG, CG (315 events)	$R_g = 0\ to\ 45\ \Omega$

Table 4.2 List of Testing Events.

These events include now system events duplicated for system loading of 20%, 60%, and 100%, as opposed to the training events that contained only 100% (nominal) feeder load. Non-fault events consist of the loads connections and disconnections, and inadvertent circuit breaker operations that are simulated at all three system loading conditions. Similarly, fault events include faults on all three different phases with three different system loading of 20%, 60%, and 100%.

The same testing set is used to test a protection package consisting of phase overcurrent (50), ground over-current (50G) and voltage restraint overcurrent relays whose functionality has been discussed in Chapter 2 as part of the considered system data. Their settings are reviewed for convenience in Table 4.3.

Device	DG A setting (A)
Inst. Overcurrent	$I_{pickup-phase} = 151$
Voltage Restraint	$I_{pickup-phase} = 6 * V_{GenA}(kV)$
Inst. Ground Overcurrent	$I_{pickup-ground} = 151$

Table 4.3 Conventional Protection Device Settings for Single DG System.

The testing set described in Table 4.2 is used to test all considered protective devices, including the IR for fault detection duty. Testing for fault type identification is done using the same testing set as for fault detection but at the exclusion of system events not containing faults. Testing for faulted phase identification is carried out on specific subsets including the appropriate fault type.

4.4 Intelligent Relay Protection Handles

The protection handles used by the Intelligent Relay are, as explained in Chapter 3, the variables implicated at the decision making nodes of the DT classifier produced during the training stage.

Despite the fact that a large number of prospective DG variables were fed to the Data Mining algorithms constructing the DT classifiers, the ones serving either one or more IR to properly fulfill the contemplated duties are summarized in Table 4.4. These variables are sufficient to address all DG contemplated three phase transformer interconnections as well.

Name	Description	Name	Description
Ia, Ib, Ic	Phase RMS Currents	Va, Vb, Vc	Phase to Ground RMS Voltages
I_1, I_2, I_0	Sequence Currents	V_1, V_2, V_0	Sequence Voltages
I_{an}, I_{bn}, I_{cn} e.g. $I_{an} = \frac{I_a}{(I_a+I_b+I_c)}$	Normalized Phase RMS Currents	V_{an}, V_{bn}, V_{cn} e.g. $V_{an} = \frac{V_a}{(V_a+V_b+V_c)}$	Normalized Phase to Ground RMS Voltages

Table 4.4 Variables used for Constructing Decision Trees

4.4.1 Intelligent Relay Logic for Fault Detection Duty

Two DT classifier design approaches were examined to satisfy Fault Detection Duty requirements. The first entailed the construction of five class classifier and the second the construction of four two class classifiers acting in parallel.

The five-class DT classifier is a multi-class approach to the Fault Detection problem with four classes reserved for the four contemplated shunt fault types, i.e. LLL, SLG, LL and LLG, and the fifth class for system events involving not faults at all.

The use of four two-class DT classifiers segments the problem and reduces it from a multi-class to a two-class problem. The four DT classifiers are each dedicated to classifying system events in two classes only, i.e. the class containing system events of a particular shunt fault type and another class containing non fault events. In other words there will be four two class classifiers, one for LLL faults, one for SLG faults, one for LL faults and one for LLG faults, with the classifier for, say, SLG faults splitting the system events in two classes one containing only SLG faults and another containing all the non fault events. These four classifiers acting in parallel will detect any type of shunt fault.

The motivation behind examining both DT classifier design approaches was not only to entertain the vital relay performance considerations but, also, the fact that two-class DT classifiers are invariably simpler in structure than multi-class classifiers thus resulting in a simpler tripping relay logic.

Multi-Class Fault Detection Decision Tree Classifiers

The multi-class DT classifiers explained above are shown in Fig. 4.2. for DG-A and for both transformer interconnections. The DT contain exclusively the handles contained in Table 4.4. It can be seen that, as expected, the Delta (DG side)-Yg (utility side) related

DT classifier uses zero sequence current to discriminate between non-fault and fault system events. It is also seen, however, that the discrimination range (threshold) LLL and non-fault events may be very small, almost impractical for an actual field relay setting. In the case of a Delta-Delta DG transformer connection the zero sequence current no longer emerges as an important variable from the data mining process but, instead, the zero sequence voltage becomes of importance, as physically expected given that ungrounded systems hardly feature any residual current flows. It is also seen that: a) the importance of zero sequence quantities is not at the same decision making levels for utility side grounded and ungrounded systems, b) positive and negative current sequences are common dominant handles in both DT classifiers and c) neither DT logic is obviously interpretable.

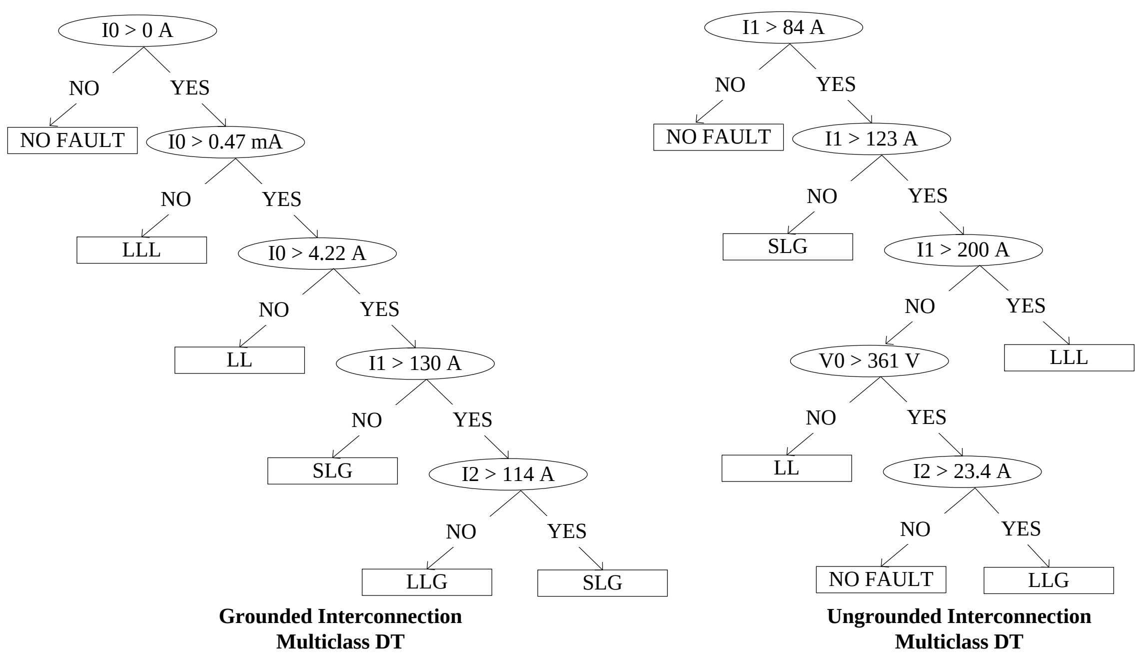

Fig. 4.2 Multi-class, Single-DG Fault Detection Duty DTs

These DTs were tested using the testing set events per Table 4.2. The resulting performance indices both SI and DI are summarized in Table 4.5. The rather poor security index (SI) for the Delta-Yg transformer interconnection in conjunction with the rather small range magnitudes (thresholds for the IR) of the corresponding DT provided an extra motivation to examine at depth the alternative two-class classifier approach.

	DI	SI
Grounded	100%	56.16%
Delta	92.95%	96.49%

Table 4.5 Performance of Multi-Class Decision Trees

Two-Class Fault Detection Decision Trees

As explained, four different DT classifiers are produced each dedicated to a separate shunt fault type. They are to be invoked in parallel and if either one categorizes the examined system event as a fault event , the system event is so labeled, irrespective of the fault type, i.e. irrespective of which DT detected it . These DTs are shown in Fig 4.3 and Fig 4.4 for both DG-A transformer interconnections.

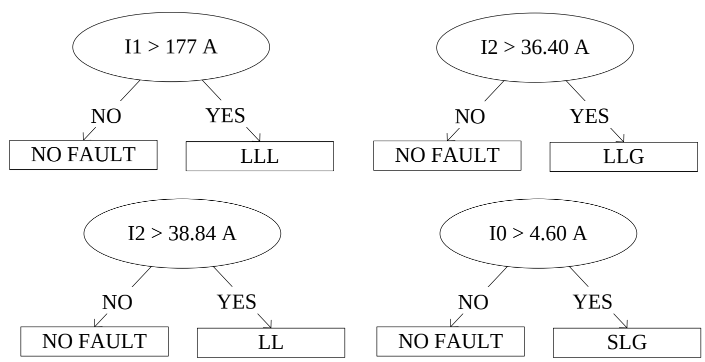

Fig. 4.3 Two-class Faults Detection Decision Trees for DG-A Yg Transformer Connection

The following comments are in order upon inspection of the resulting DTs:

1. The resulting DT classifiers are much simpler in structure and more apt to human interpretation
2. For the grounded interconnection, LLL faults are discriminated against non-fault events using the positive sequence current as handle.
3. For the grounded interconnection, LL and LLG fault are distinguished through the handle of negative sequence current due to the unbalance created at the fault position

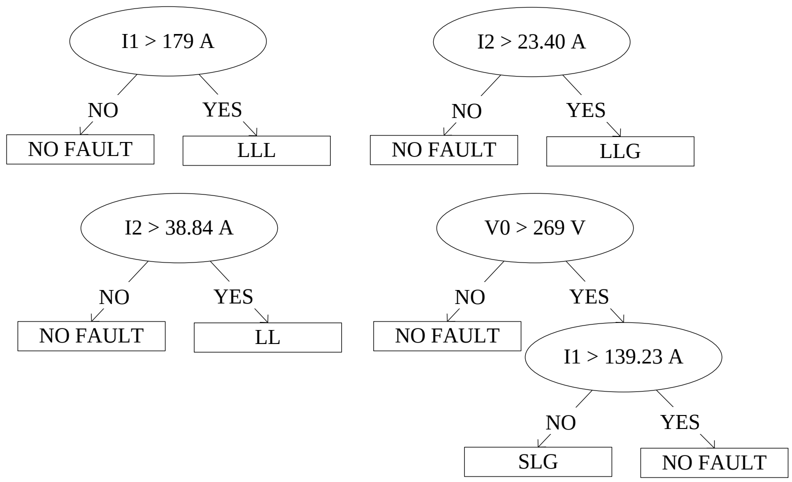

Fig. 4.4 Two-class Faults Detection Decision Trees for DG-A Delta Transformer Connection

4. For the grounded interconnection, SLG faults are discriminated through the zero sequence current threshold, as expected

5. For the ungrounded interconnection, LL and LLG faults are similar in the sense that, in the absence of zero sequence current, they both use the negative sequence current handle albeit with different range (threshold)

6. For the ungrounded interconnection, SLG fault detection involves the zero sequence voltage handle.

These decision trees are tested on different 1365 non-fault and fault testing events and Dependability and Security Indices are determined. These indices are compared to those of conventional protection. The comparison for the grounded interconnection protection is provided in the Table 4.6.

It is seen that the intelligent relay features higher performance indices than the considered conventional protective devices for all four types of faults, the sole exception being the marginally smaller DI index of the LLL faults. This performance index behavior is retained not only for the DTs dedicated to specific fault types but for overall package-level performance as well, in compliance with the outlined logic of parallel functioning two-class decision trees.

	Intelligent		Conventional	
	DI	SI	DI	SI
LLL	99.18%	98.25%	100%	96.49%
LL	100%		98.40%	
LLG	100%		99.47%	
SLG	99.68%		80.00%	
Total	99.77%	98.25%	94.65%	96.49%

Table 4.6 Dependability and Security Indices for Grounded Interconnection

Further examination of the obtained results, revealed that the type of faults responsible for the increased IR performance are the high-resistance and/or end-feeder SLG faults. More specifically, Fig. 4.5 below, gives the dependability index resulting from SLG fault detection for both the IR and the conventional protective devices package, for SLG faults in terms of the prospective fault resistance. It can be seen there that the conventional protective devices package can yield a dependability index as low as 60 % for ground resistances higher than 40 Ω.

Similar results are shown for the case of a Delta-Delta DG transformer interconnection in Table 4.7. For this case, however, the relative performance of the IR is even better retaining a significant edge for SLG faults.

	Intelligent		Conventional	
	DI	SI	DI	SI
LLL	100%	100%	100%	96.49%
LL	100%		98.40%	
LLG	100%		98.40%	
SLG	99.37%		35.87%	
Total	99.85%	100%	84.14%	96.49%

Table 4.7 Dependability and Security Indices for Delta Interconnection

4.4.2 Fault Type Classification Decision Tree Classifiers

As already stated these DTs are produced using the fault system training events of the basic training set and can be seen in Fig 4.6 for both DG transformer interconnections.

The following observations are made:

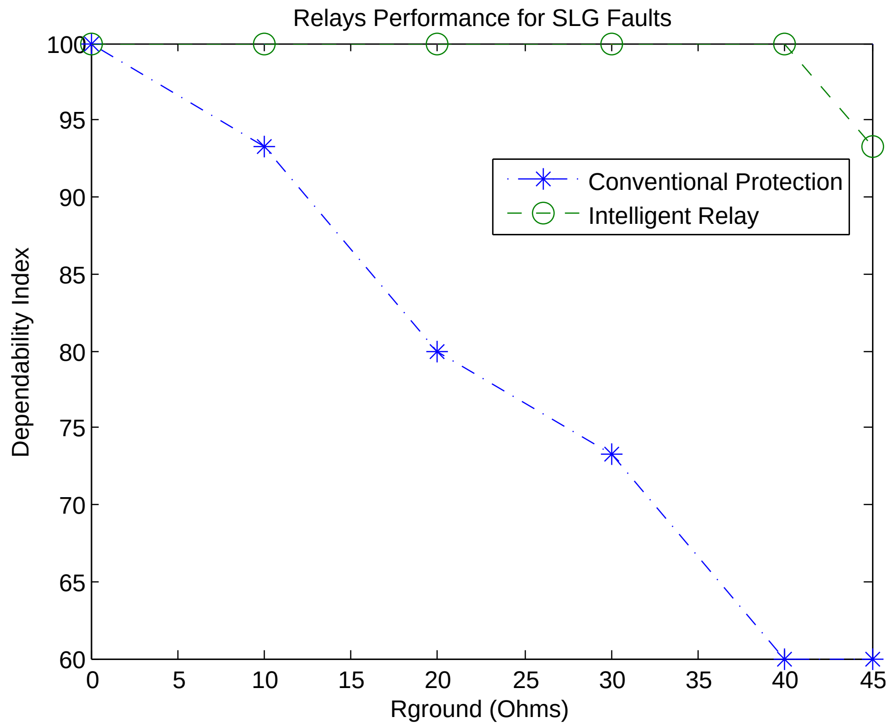

Fig. 4.5 Conventional and Intelligent DI for SLG faults

1. The grounded interconnection DT is similar to the multi-class one resulting from the multi-class shunt fault detection approach at the exclusion of the class reserved for non-fault system events, i.e. it is a four-class DT.

2. The grounded interconnection DT is composed exclusively from sequence fault current elements that identify the various fault types. The root decision node range can be replaced by zero value threshold if deemed impractical without adverse effects on IR performance.

3. The ungrounded interconnection DT assumes a rather simpler structure that, also includes the zero sequence voltage as a protection handle. The root decision node range can, again, be replaced by a zero value threshold.

4. Both DTs can be produced using the multi-class approach

These decision trees are tested on 1308 test fault events yielding an overall accuracy of 92.12 % and 94.80 % respectively.

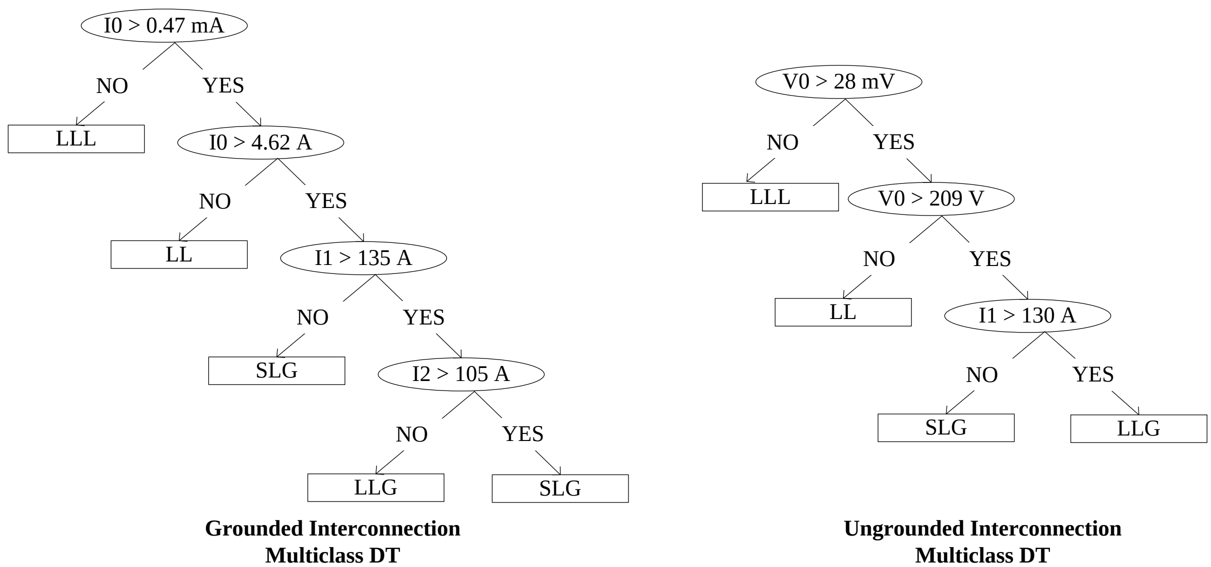

Fig. 4.6 Fault Classification Decision Trees

4.4.3 Faulted Phases Identification Decision Tree Classifiers

These DT classifiers are invoked once a fault type has already been determined. Given that this task becomes trivial for the case of LLL faults, these DT classifiers are produced as three distinct three class classifiers (one for SLG, one for LL and one for LLG faults) using as a training set for each of them the subset of the fault system events pertaining to that particular fault, albeit augmented with identical events on the remaining phases. The resulting DTs for grounded and ungrounded DG transformer interconnection are shown in Figs 4.7 and 4.8 respectively. These DTs use the normalized voltage and current variables per Table 4.4. Both DTs were tested on respective fault type events. Barring the LLG fault type for the grounded interconnection that exhibited a phase recognition accuracy of 99.63 %, all the remaining DTs correctly identified the phases involved in all the remaining fault types.

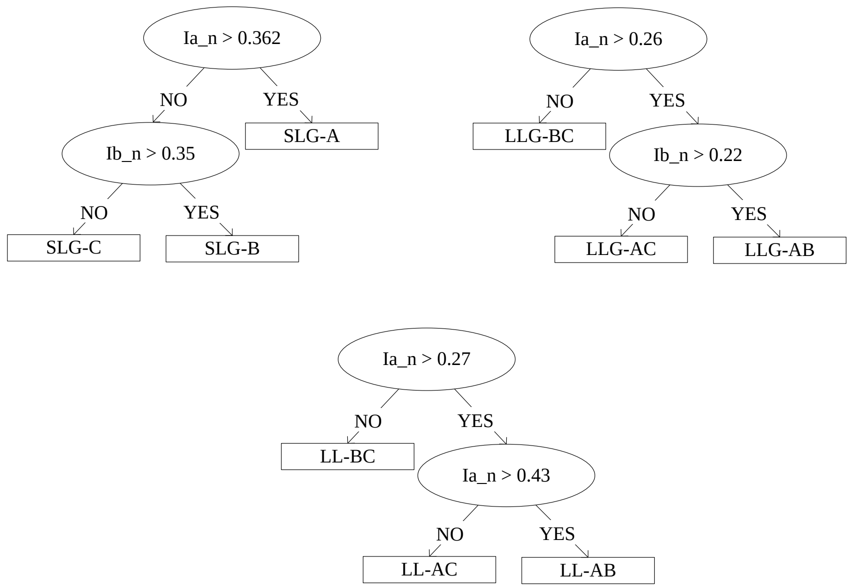

Fig. 4.7 Faulted Phase Classification Decision Trees for Yg Transformer

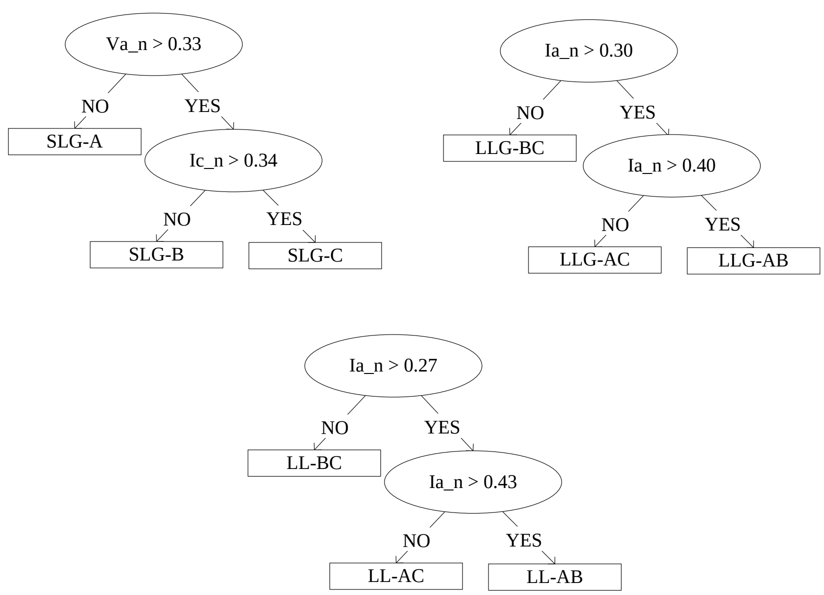

Fig. 4.8 Faulted Phase Classification Decision Trees for Delta Transformer

4.5 Intelligent Relay (IR) Detection Logic and Results Summary

Based on the contents of this chapter, the block diagram summarizing the functionality of the Intelligent Relay for both shunt fault detection and recording functions is summarized in Fig. 4.9 below.

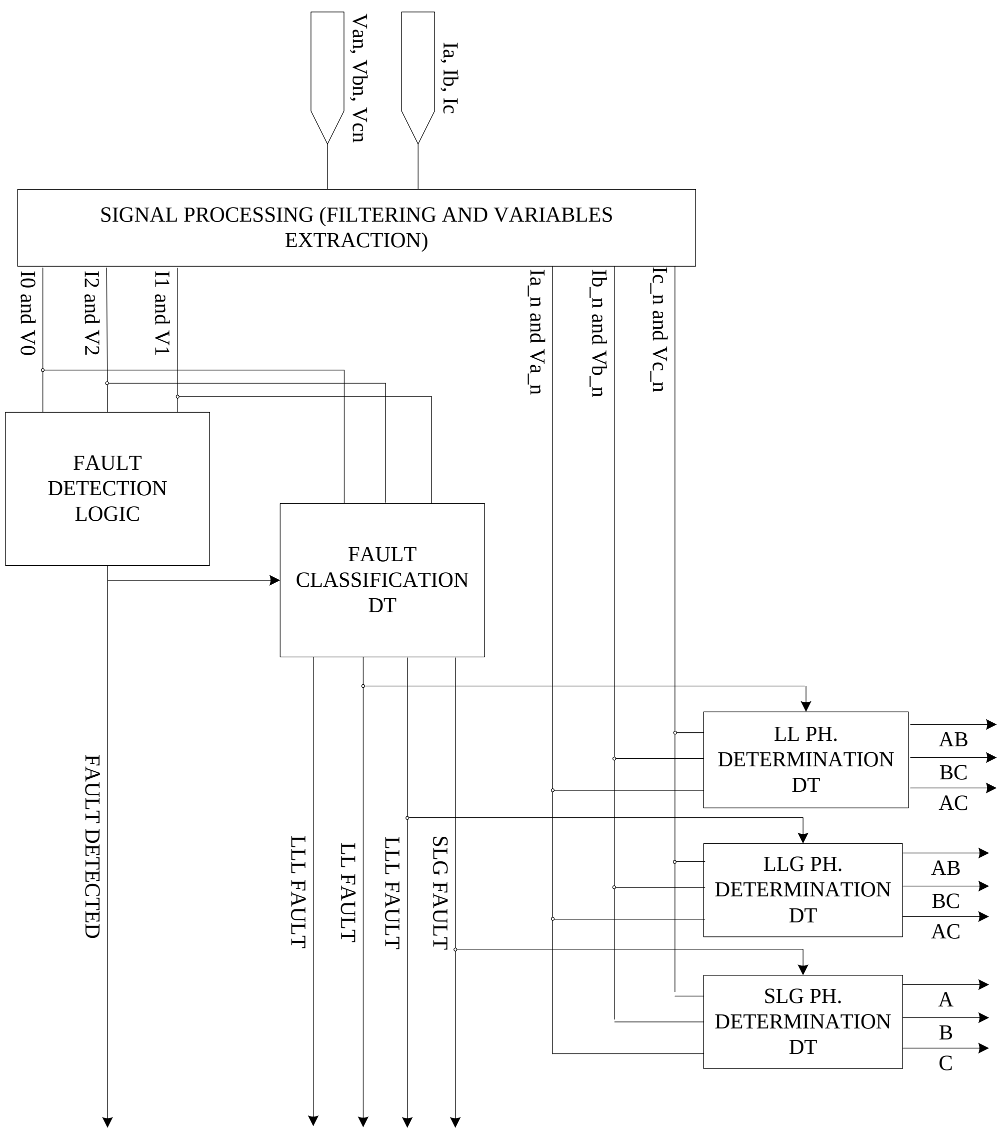

Fig. 4.9 Relay Logic Diagram for Single DG Distribution System

And, the IR performance is summarized in Table 4.8 for reference convenience.

		Grounded	Delta
Fault Detection	Dependability Index	99.77 %	99.85 %
	Security Index	98.25 %	100 %
Fault Classification		92.12 %	94.80 %
Faulted Phase Detection	LL	100 %	100 %
	LLG	99.63 %	100 %
	SLG	100 %	100 %

Table 4.8 Intelligent Relay Performance for Single DG Distribution System

4.6 Conclusions

This chapter has demonstrated that data mining can be successfully used to detect area-EPS faults by the DG fault interconnection protection. Furthermore, it demonstrated that the same methods can be used to identify the type of area-EPS fault and the implicated system phases for recording purposes. The intelligent relay was also found to exhibit a noticeably higher dependability in detecting high-resistance ground faults.

Chapter 5

Fault Interconnection Protection using Intelligent Relays for Multiple DGs

This chapter extends the methodologies and techniques developed in Chapter 4 for a single DG to multiple DGs, thus establishing the feasibility of the proposed approach to dispersed synchronous generation. The distribution system used has already been described in Chapter 2 but is reproduced here, at the Single-Line Diagram level, for ease of reference. It is the same test-bench feeder used in the previous chapter except that two more DGs are now connected. First, the effect of the multiple DGs on the pre-fault steady state DG currents is reviewed. Then, the effect of the presence of multiple DGs on the DG fault current contributions is assessed in order to illustrate the significant qualitative and quantitative impact the presence of additional DGs may entail on the fault current contributions of a DG, otherwise acting alone. Intelligent Relays are then set for all three DGs based on the already developed methodologies and techniques.

5.1 Multiple DG Distribution Test Feeder

The distribution system with three DGs can be seen in the Fig. 5.1. This is the same system as described in the last chapter but it has two additional synchronous generators added. Generator A has the same variables as before and supplies 30 % of the system load. Generator B and Generator C have capacities of 3 MVA and 4.5 MVA respectively. Gen A is studied with Delta-Yg and Delta-Delta transformer interconnections. The Gen B transformer interconnection is Delta (DG side) Yg (utility side) with a 20 Ω impedance, while Gen C interconnection transformer is Delta-Delta connected. The 20 Ω grounding impedance has been considered in order to comply with usual DG utility-side practices recommending this impedance as a typical value for reaching a compromise between the total absence of grounding impedance and a solidly grounded case (see also Chapter 2).

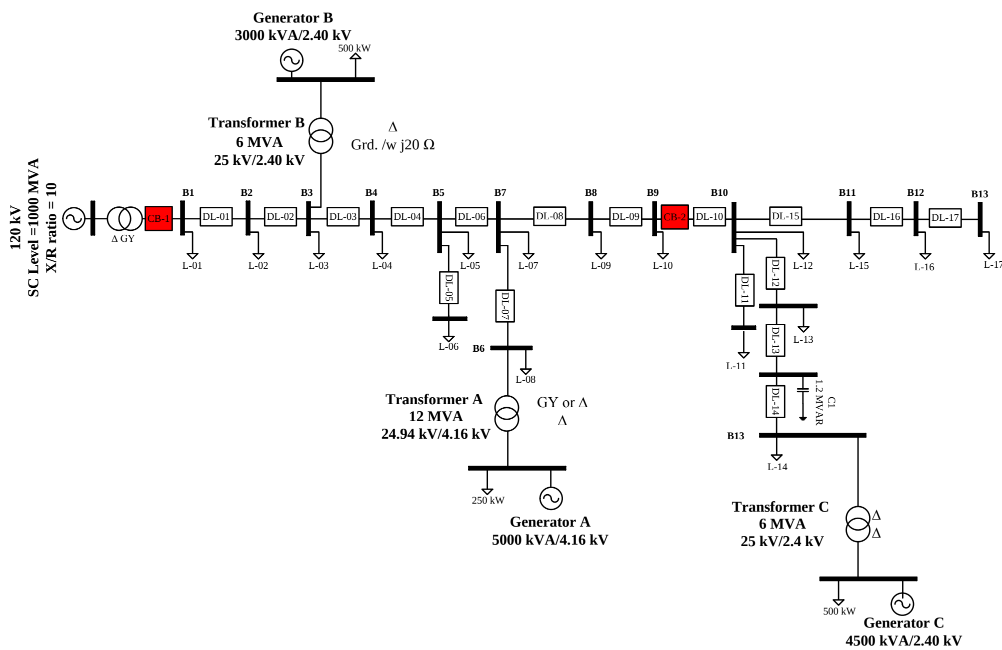

Fig. 5.1 Multiple DG Distribution System (Reproduced from Chapter 2)

The steady state results are displayed in Table 5.1, where it is seen that Gen A supplies smaller current and has higher PCC voltage in the multiple DG distribution system, as opposed to the DG-A acting alone for all three loading conditions. This can be explained by the fact that the other two DGs PQ contributions result in elevated voltage levels while its active and reactive power production is unchanged.

System Loading		Substation Measurements		DG A Measurements		DG B Measurements		DG C Measurements	
%age	(MVA)	V (kV)	I (A)	V (kV)	I (A)	V (kV)	I (A)	V (kV)	I (A)
20%	2.26	26.50	43.02	27.22	12.98	27.40	29.38	26.70	37.46
60%	6.79	26.36	57.47	26.60	43.67	26.51	31.20	26.39	38.18
100%	11.31	26.20	118.80	25.86	75.60	25.61	33.15	26.05	38.99

Table 5.1 System Normal Condition Voltages and Currents

5.1.1 Impact of Multiple DGs on DG Fault Current Contributions

This section illustrates the impact of multiple DGs on the Gen A fault current contributions in comparison to the same contributions, had the DG been acting alone in the system. Additional DGs not only change the pre-fault conditions (see Table 5.1) but also change the network topology resulting in different fault current flow patterns. The impact on fault current contributions can be seen in the Figs. 5.2, 5.3, and 5.4. All of the faults simulated therein have an arc impedance of 2 Ω and a ground impedance of 20 Ω, while assuming a 100 % system loading for both grounded and delta Gen A transformer interconnection.

LLL Fault Current Contributions: The Gen A positive sequence current contributions to LLL faults along the feeder are shown in Fig. 5.2. It is noticed that Gen A current contributions are smaller in the multiple DG system with exception of a small area in the network that is between Gen A and Gen B.

LL and LLG Fault Current Contributions: Both LL and LLG fault currents were found to be characterized by the presence of negative sequence currents. The Gen A negative sequence current contributions behavior to both LL and LLG faults is similar, thus only the LLG fault current profile is shown in Fig. 5.3. The negative sequence current contributions from Gen A in the 3 DG system are, in general, smaller than the corresponding ones for the 1 DG system for both Gen A grounded and ungrounded interconnections.

SLG Fault Current Contributions: The Gen A zero sequence current and voltage contributions are provided in the Fig. 5.4 for SLG faults. The Gen A ungrounded interconnection does not have a zero sequence current element, that is why zero sequence voltages are shown instead. It is also seen that the Gen A zero sequence contributions increase for SLG faults downstream of the Gen A, a fact that is also due to the fact that the Gen C interconnection transformer is ungrounded.

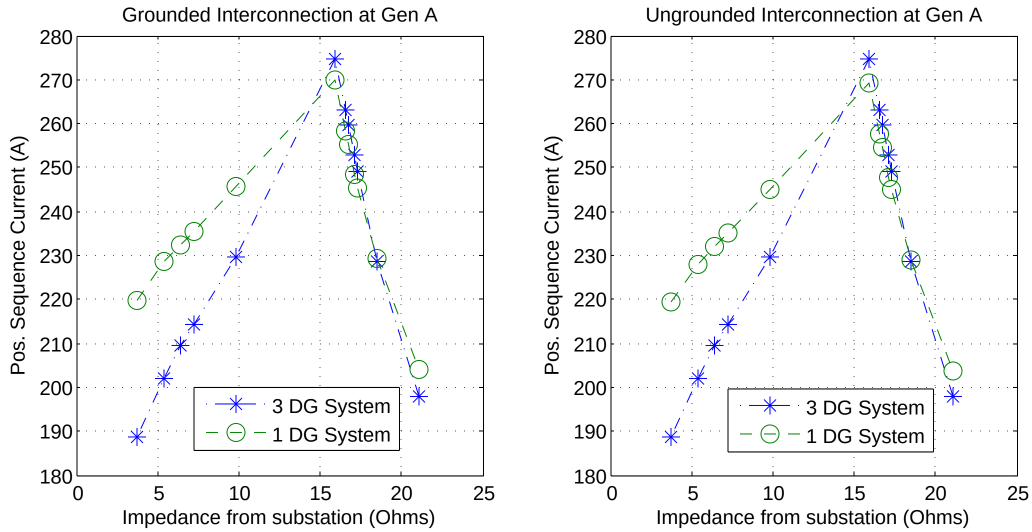

Fig. 5.2 Gen A LLL Fault Current Contributions

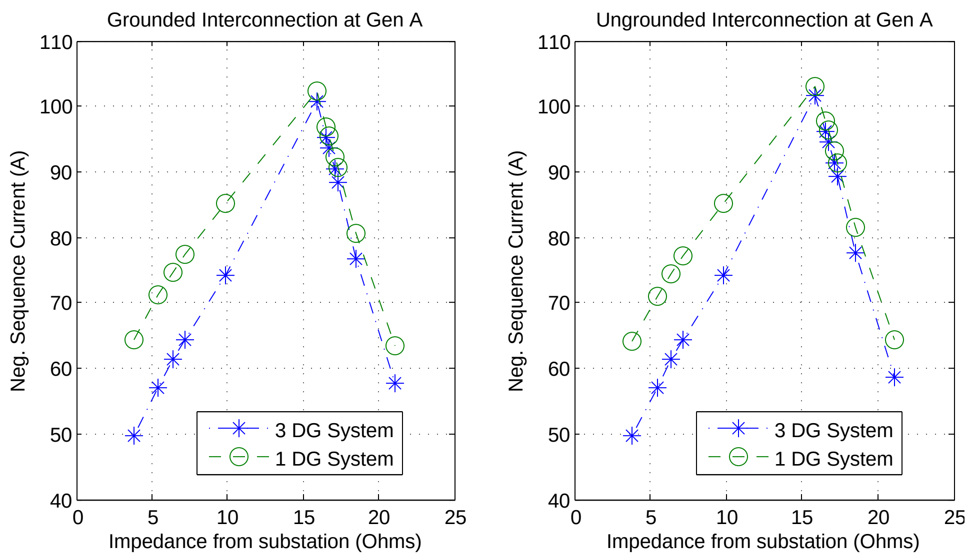

Fig. 5.3 Gen A LLG Fault Current Contributions

5.2 Intelligent Relays Setup on Dispersed DGs

Intelligent relays can be set for all dispersed DGs by employing the same methodologies and techniques introduced in Chapter 4 for a single DG. The resulting IR logic for each connected DG still follows the basic functional diagram outlined in Chapter 4 which is reproduced here, for easier reference, in Fig. 5.5. Different processed attributes are passed to

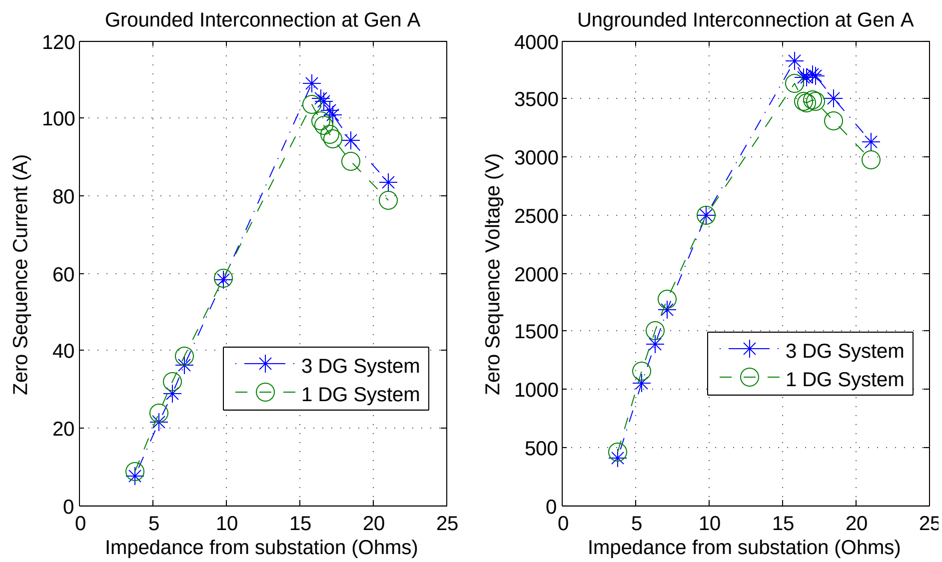

Fig. 5.4 Gen-A SLG Fault Current Contributions

the decision trees inside the fault detection logic, fault classification, and phase determination logic blocks, and the decision trees detect the faults, provide fault type and the faulted phases. This IR logic is applied to each of the three synchronous generators. It is important to stress that fault detection relays must be trained separately for each connected DG given that the same area-EPS fault is perceived to be quantitatively and qualitatively different by each DG depending on its proximity to the fault and on the winding connections of its interconnecting transformer.

5.3 Training Events

The training set of system events does not change in the presence of multiple DGs since it contains system events independently of the DG multiplicity the feeder experiences. The same system events, however, are perceived differently by each connected DG as explained in the previous section. This necessitates dedicated Intelligent Relay training, for both fault detection and recording duties for every connected DG. In other words, the training procedure needs to be carried out independently for every connected DG based on data collected for every DG for any given system event. The description of the training set has already been described in Chapter 4 and will not be repeated here. It is simply mentioned that, all training system events are taken at 100% system loading, again, as for a single

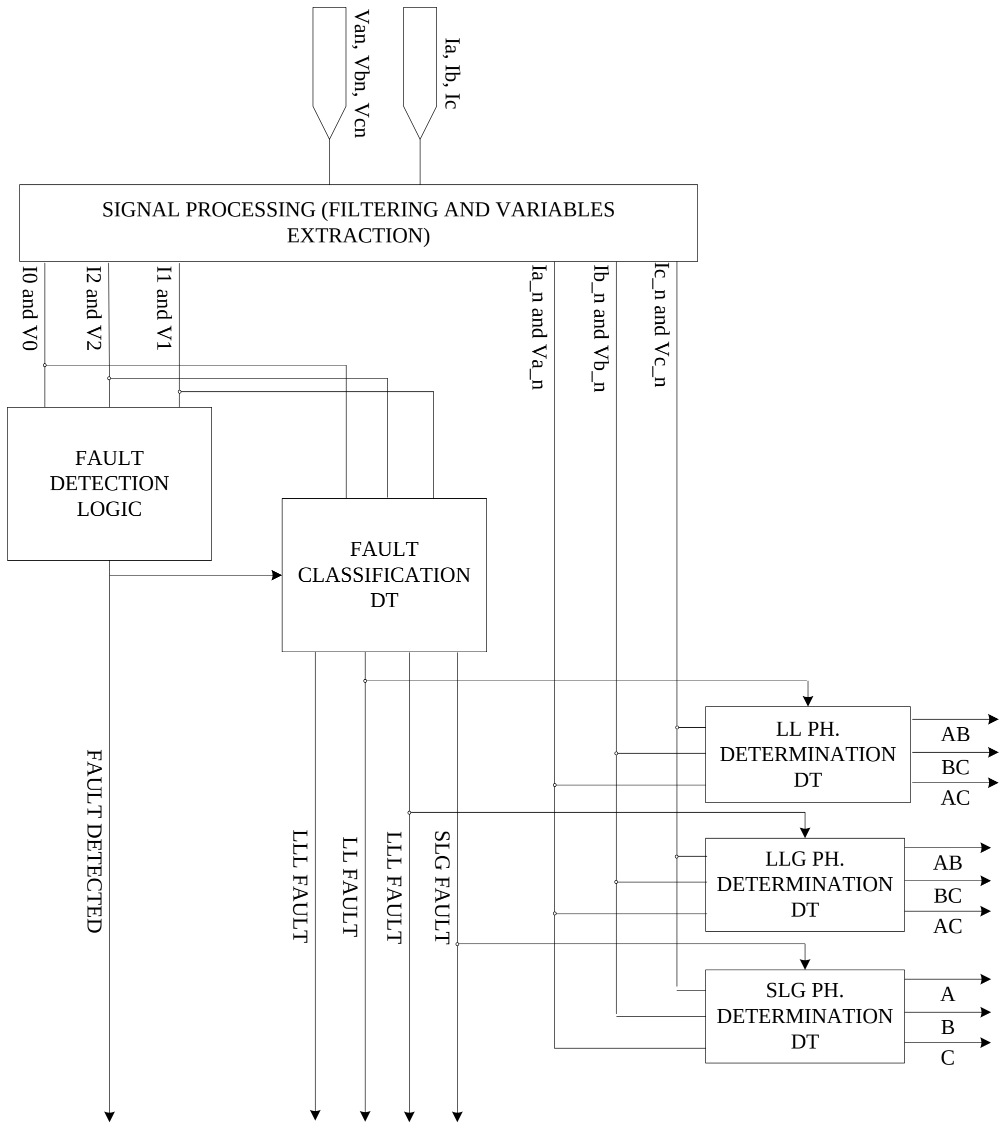

Fig. 5.5 Individual DG Relay Functional Block Diagram

DG.

The training process for recording duty also follows the same procedures as for the single DG case both for fault type and faulted phases identification purposes, also clearly outlined in Chapter 4.

5.4 Testing Description

The same testing sets for fault-detection, shunt fault type and faulted phase identification used for the single DG are used for multiple DGs as well since for the multiple DG case, their IRs must also be tested for feeder incidents here. As the for the case of a single DG, the testing set comprises system loading of 20 %, 60 %, and 100 % in terms of the nominal feeder load level. It is reminded that these events are all events not included in the training set. The detailed description of the testing sets has been addressed in Chapter 4.

In terms of the settings of the conventional protective devices some modifications are, however, warranted based on the slightly different steady state currents obtained for the base loading case of 100 % feeder load, while the basic setting philosophy followed in Chapter 4 is adhered to. The corresponding quantitative changes are summarized in Table 5.2.

Device	DG A setting (A)	DG B setting (A)	DG C setting (A)
Inst. Overcurrent	$I_{pickup-ph} = 151$	$I_{pickup-ph} = 66$	$I_{pickup-ph} = 75$
Voltage Restraint	$I_{pickup-ph} = 6 * V_{GenA}$	$I_{pickup-ph} = 2.7 * V_{GenB}$	$I_{pickup-ph} = 3 * V_{GenC}$
Inst. Ground Overcurrent	$I_{pickup-grd} = 151$	$I_{pickup-grd} = 66$	$I_{pickup-grd} = 75$

Table 5.2 Conventional Protection Devices Settings

5.5 Decision Tree classifiers for Multiple DGs

In what follows, the DT classifiers obtained for all three DGs are given. The same techniques were used for all three of them and their DT classifiers can easily be obtained during parallel processing since they all need the same set of training sets and no serial processing is involved.

First, the fault detection DTs are given for all three DGs. Then the DTs addressing fault recording needs are portrayed along with pertinent performance considerations.

It is reminded that DTs are given for DG-A under both Delta-Yg and Delta Delta DG transformer interconnections. DG-B and DG-C are assumed Delta Y-impedance grounded and Delta-Delta connections respectively.

Multi-Class Fault Detection Decision Trees

Multiclass DTs are first constructed based on the first approach already outlined in Chapter 4 that considers four classes for the four fault types and a separate class for non fault events. The DG-A DTs for grounded and ungrounded utility side transformer connections can be seen in the Fig. 5.6. It is seen that the same general features are encountered as the similar DTs obtained when the DG with the utility side grounded DT features only current, while the delta utility side related DT features zero sequence voltage.

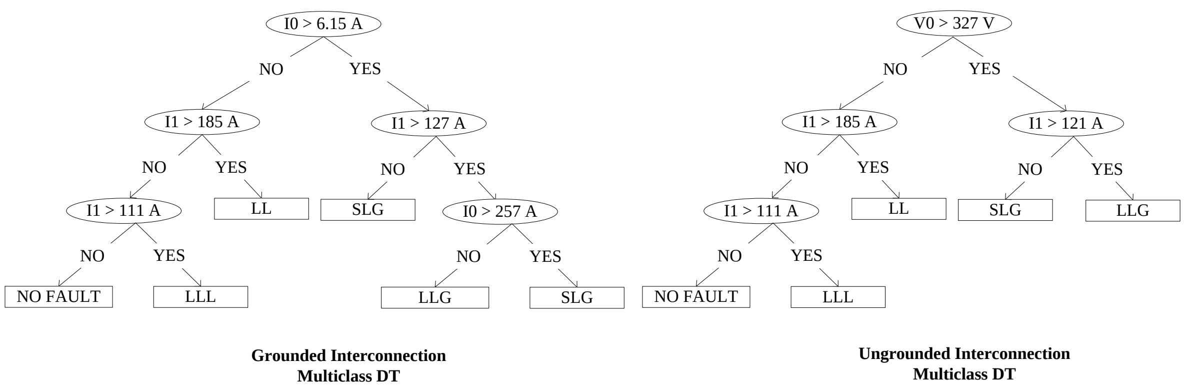

Fig. 5.6 DG-A Multi-class Fault Detection DTs in the Presence of Multiple DGs

The performance indices of these DTs are shown in Table 5.3. It is seen that now the multi-class DTs do not suffer from low security indices as for the single DG case, while their resulting thresholds are quite within a practical range. There is still motivation however, to resort to two-class classifiers in view of their rather complex structure. Similar DTs can be obtained for the other two connected DGs.

	DI	SI
Grounded	91.61%	100%
Delta	95.63%	100%

Table 5.3 Performance of Multi-Class Decision Trees

Two-Class Fault Detection Decision Trees

In compliance with the procedure followed when DG-A was acting alone, four two-class DTs are obtained. It is reminded that these DTs are constructed for the four particular shunt types and, by design, they each classify system events into two classes, i.e. their own fault type and non-fault events. They are invoked in parallel and if either one of them detects a fault, the system event is characterized as a fault event. These DTs for a utility-side grounded DG-A interconnection can be seen in the Fig. 5.7. The corresponding floating point utility side DTs are the same with the sole exception that the SLG detection threshold, which is still the negative sequence current increases to 6.93 A from 6.88 A.

It is emphasized that these DTs are different from those produced in the single DG distribution system. The LLL positive sequence (phase) current threshold is smaller than the 1-DG distribution system. An important qualitative difference with respect to the 1-DG DTs is that now negative sequence, and not zero sequence, is the SLG detection handle. The reason for that is that the zero sequence currents become decreasingly important due to blinding effects caused by the very location of the DG.

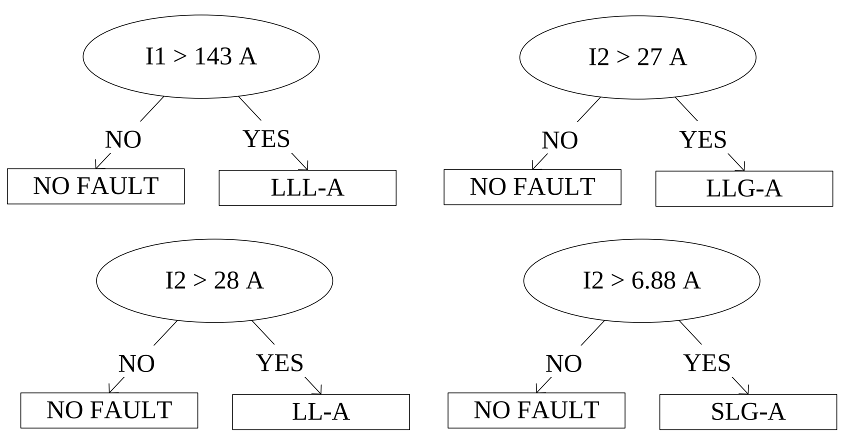

Fig. 5.7 Gen A Fault Detection Decision Tree for Gen A transformer GrdY connection

Similar DTs can be produced for the other two DGs for both DG-A transformer interconnections and they are shown in Figs. 5.8 and 5.9 for DG-B and Figs. 5.10 and 5.11 for DG-C.

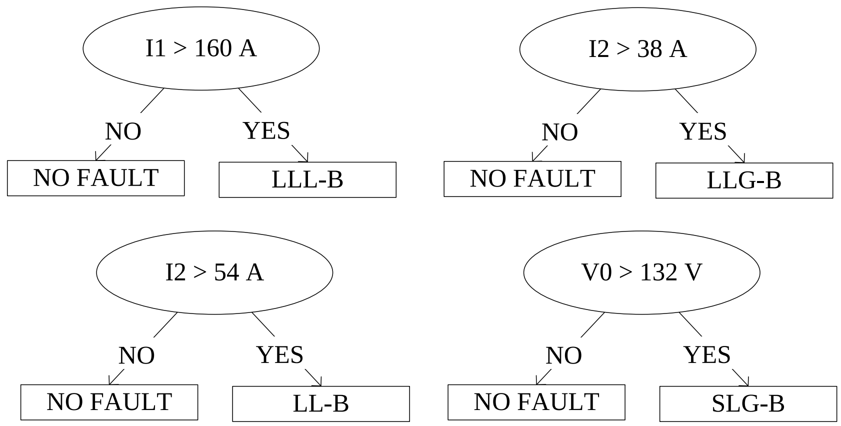

Fig. 5.8 Gen B Fault Detection Decision Tree for Gen A transformer GrdY connection

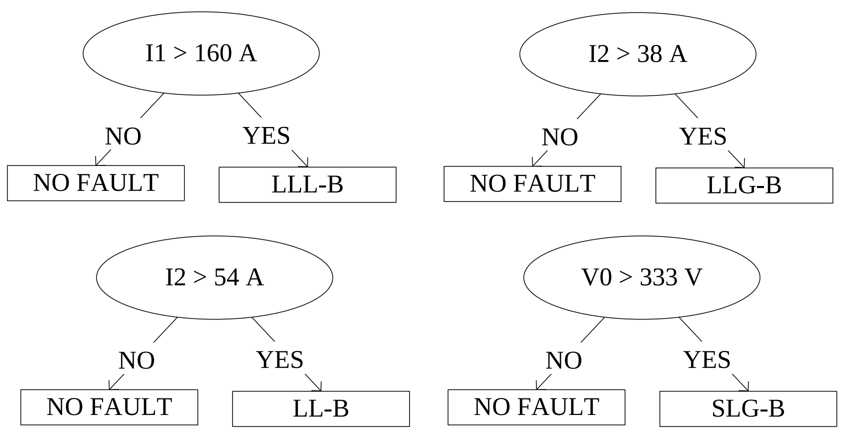

Fig. 5.9 Gen B Fault Detection Decision Tree for Gen A transformer Delta connection

These decision trees are tested on different non-fault and fault testing events and Dependability and Security Indices are determined. These indices are compared to that of conventional protection. The IR fault detection performance indices for all DGs are shown in Table 5.4 for both DG-A transformer interconnections. The intelligent relay performs better than the conventional protection for all four different types of faults.

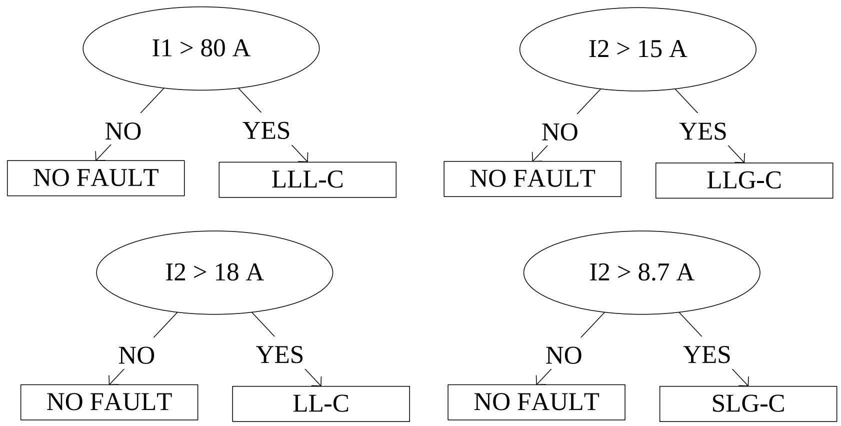

Fig. 5.10 Gen C Fault Detection Decision Tree for Gen A transformer GrdY connection

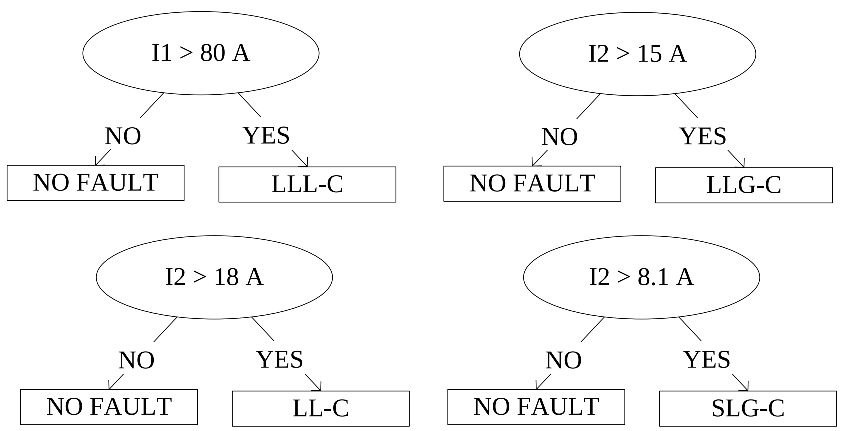

Fig. 5.11 Gen C Fault Detection Decision Tree for Gen A transformer Delta connection

5.5.1 Fault Classification IR Settings for Multiple DGs

Multi-class fault type classification trees were produced for all three DGs and for both DG-A transformer configurations. These DTs can be seen in Fig. 5.12, 5.13 and 5.14 for DG-A, DG-B and DG-C. The fault type identification performance indices are summarized in Table 5.5 for all three DGs.

Fault Type DG-A 1-Yg 1-Delta	DG-A		DG-B		DG-C	
	IR DG/SI in pu	CONV DG/SI in pu	IR DG/SI in pu	CONV DG/SI in pu	IR DG/SI in pu	CONV DG/SI in pu
LLL-1	1/1	1/1	1/1	1/.99	1/1	1/.99
LLL-2	1/1	1/1	1/1	1/.99	1/1	1/.99
LL-1	1/1	.92/1	.99/1	1/.99	1/1	1/.99
LL-2	1/1	.92/1	1/1	1/.99	1/1	1/.99
LLG-1	1/1	.96/1	1/1	1/.99	1/1	1/.99
LLG-2	1/1	.92/1	1/1	1/.99	1/1	1/.99
SLG-1	.97/1	.73/1	.99/1	.88/.99	.89/1	.59/.99
SLG-2	.97/1	.20/1	1/1	.88/.99	.89/1	.59/.99
Total-1	.99/1	.89/1	1/1	.97/.99	.97/1	.78/.99
Total-2	.99/1	.74/1	1/1	.97/.99	.97/1	.78/.99

Table 5.4 Protective Devices Performance, Fault Detection Duty

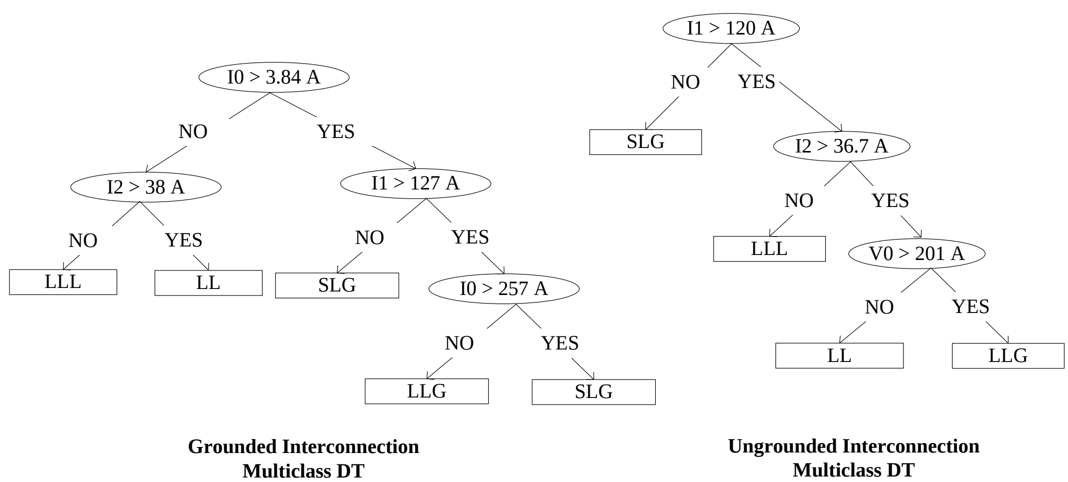

Fig. 5.12 Gen-A Fault Classification Decision Tree

The misclassification error for the utility-side grounded transformer interconnection of DG-A is manifested as 76 events misclassified out of a total of 870 testing events. This is due to the fact that, usually, LLG events are misclassified as SLG events. There are also

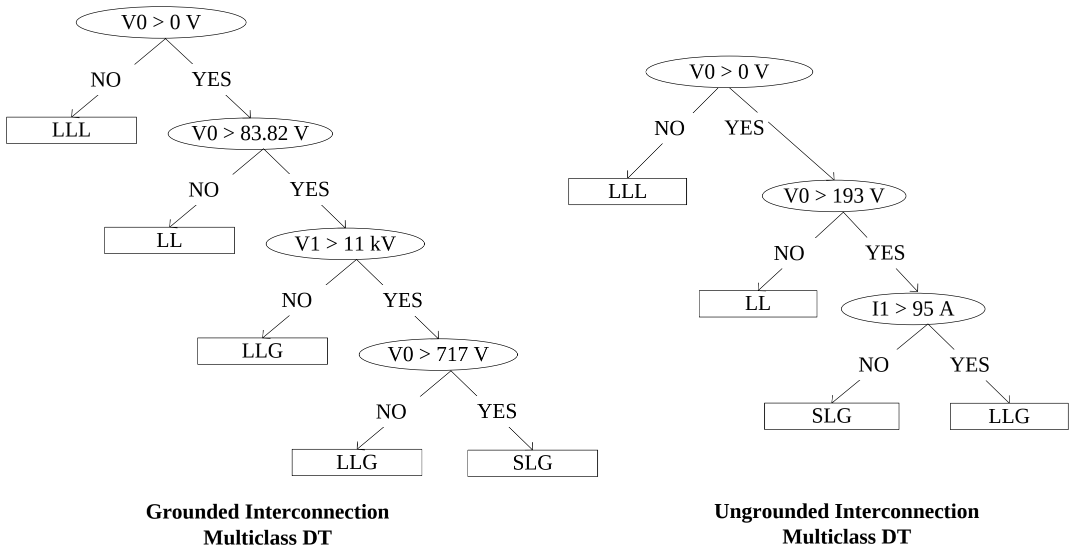

Fig. 5.13 Gen-B Fault Classification Decision Tree

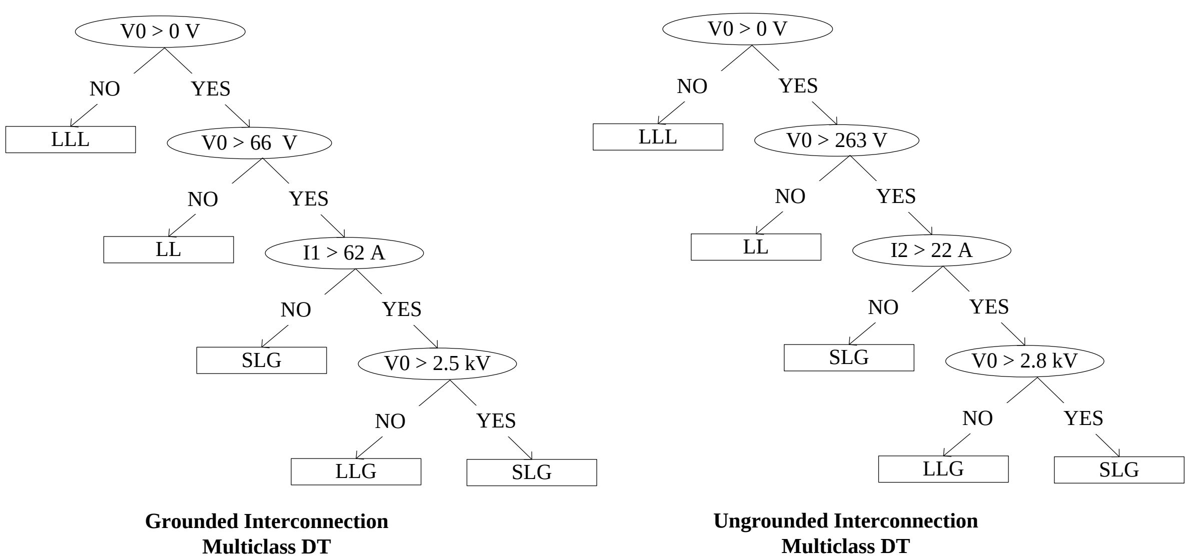

Fig. 5.14 Gen-C Fault Classification Decision Tree

	DG-A in pu	DG-B in pu	DG-C in pu
DG-A Grd-Y transformer	.87	.93	.97
DG-A Delta transformer	.90	.99	.96

Table 5.5 Protective Devices Performance, Fault Classification Accuracy Rates

only two more cases, namely: a) only one LLL-fault is misclassified as being a LLG event and b) one SLG-fault is misclassified as being a LL fault.

The misclassification error for the utility-side ungrounded transformer interconnection of DG-A reduces the corresponding dependability index to 90.34 % of the fault events within the testing set. The DT tree misclassifies 50 LL faults as SLG and 34 LLG as SLG out of total of 870 testing events. Similar considerations apply for the remaining two DGs.

5.5.2 Faulted Phases Identification

The second IR desirable type recording duty is faulted phase identification. Again, as for the single-DG case, this type of task is carried out after fault type recognition. The problem is segmented into two-class DTs each dedicated to recognize faulted phases of a particular fault type. Since the task is not applicable to LLL faults, involving all three phases, no LLL DTs are produced. Both the training and the testing set composition follows the guidelines already stipulated in Chapter 4 for a single-DG given that both sets contain feeder events irrespective of the number of the connected DGs.

Last step of the intelligent protection is to identify the faulted phases. When a fault is classified, the fault phase identification decision tree is invoked. Each fault type other than LLL has its own decision tree trained using only those fault events with faults simulated on all possible faulted phases.

Figs. 5.15 and 5.16 show the corresponding DTs for both DG-A transformer interconnections. Figs. 5.17 and 5.18 show similar DTs for DG-B, while Figs. 5.19 and 5.20 illustrate the DTs for DG-C. All three DGs DTs use normalized variables.

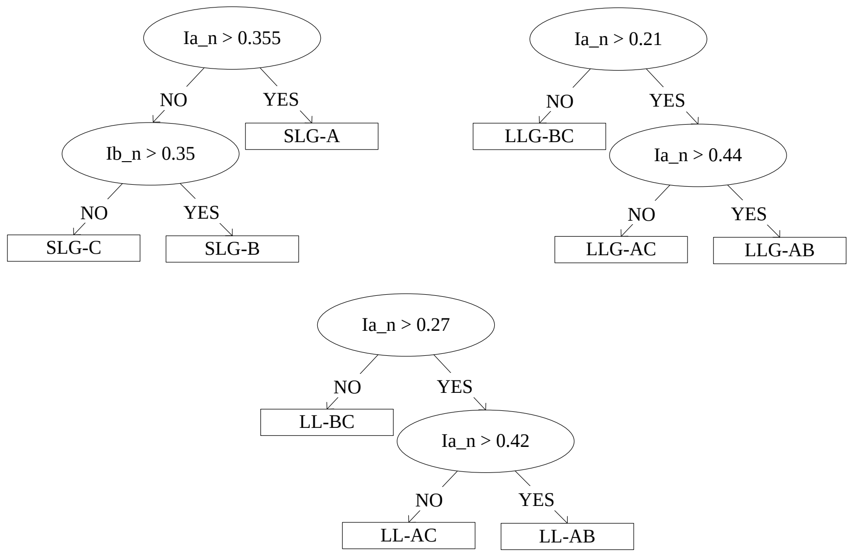

Fig. 5.15 Gen A Faulted Phase Identification for Gen A GrdY Transformer Connection

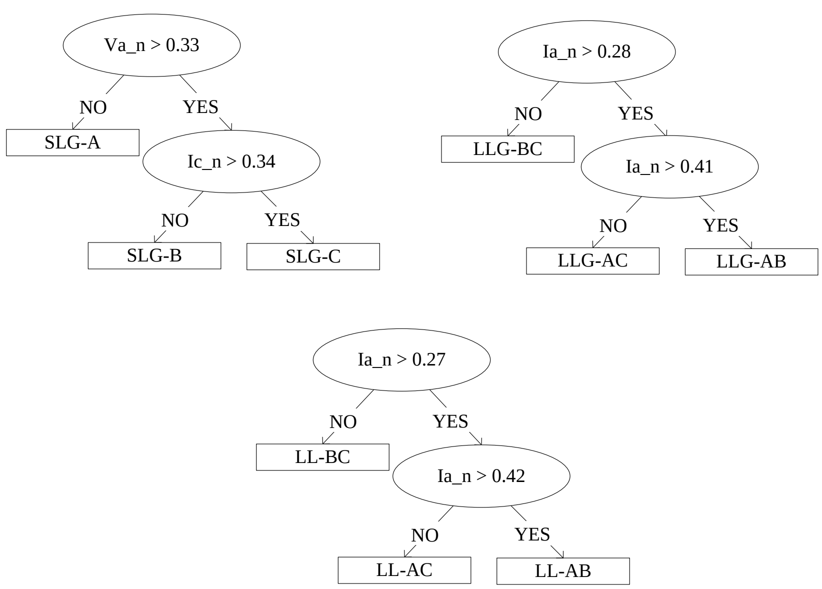

Fig. 5.16 Gen A Faulted Phase Identification for Gen A Delta transformer connection

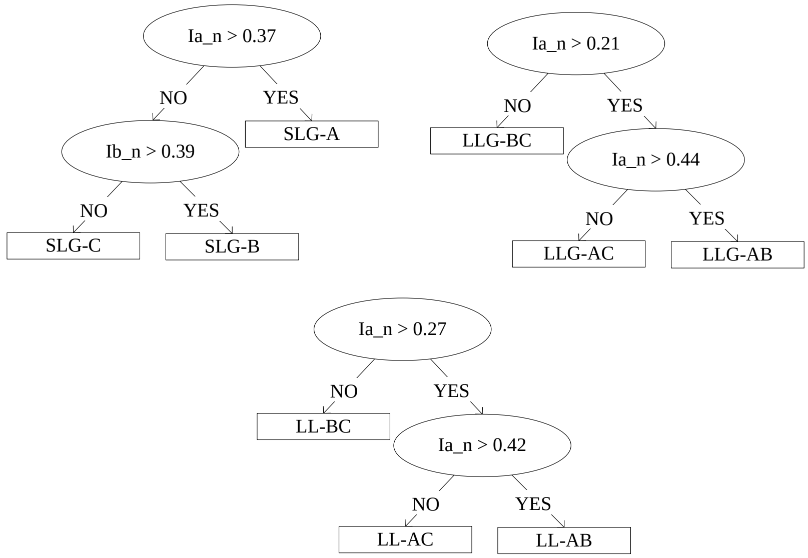

Fig. 5.17 Gen B Faulted Phase Identification for Gen A GrdY transformer Connection

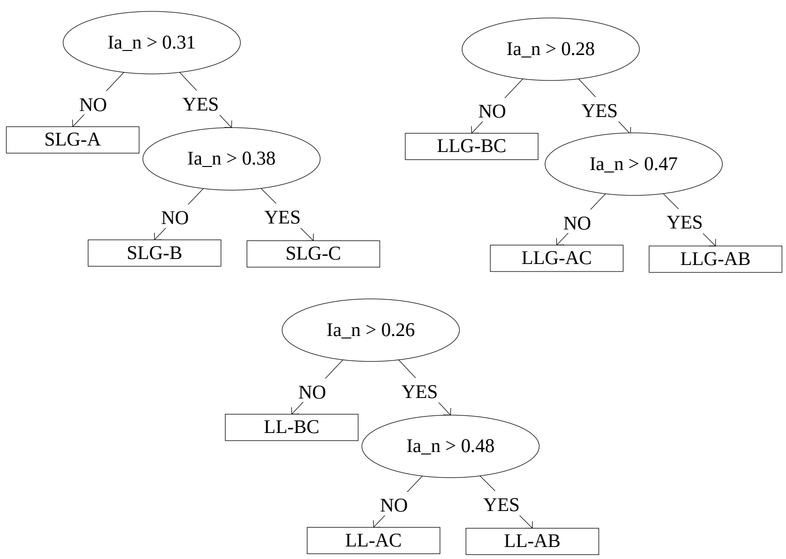

Fig. 5.18 Gen B Faulted Phase Identification for Gen A Delta transformer Connection

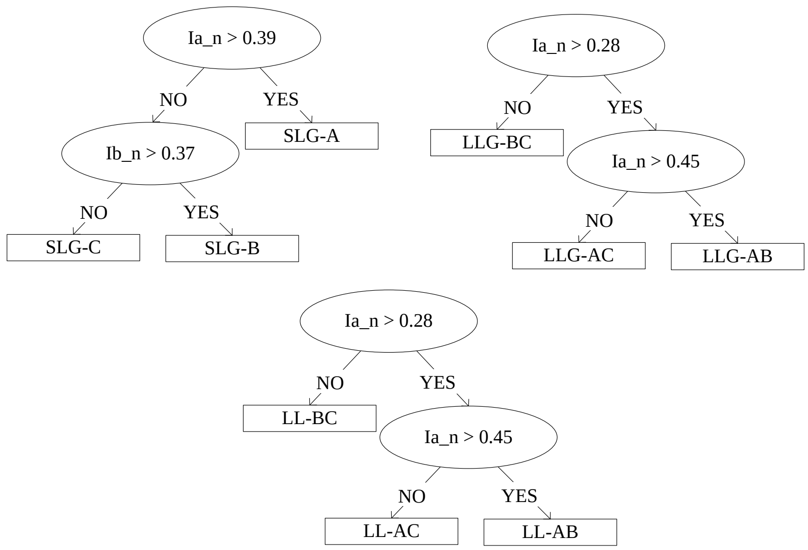

Fig. 5.19 Gen C Faulted Phase Identification for Gen A GrdY transformer Connection

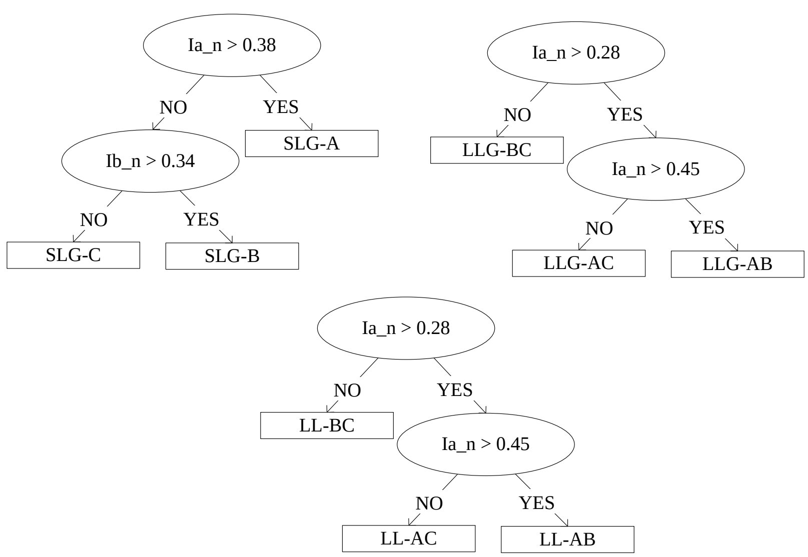

Fig. 5.20 Gen C Faulted Phase Identification for Gen A Delta transformer Connection

The performance of these DTs was tested against the standard testing set involving all fault types and faulted phases of any combination. Their performance is summarized in Table 5.6.

Fault Type DG-A 1-Yg 2-Delta	DG A	DG B	DG C
SLG-1	1	1	.99
SLG-2	1	.91	1
LL-1	1	1	1
LL-2	1	1	1
LLG-1	.99	1	1
LLG-2	1	1	1

Table 5.6 IR Fault Phase Identification Performance

5.6 Conclusions

This chapter has demonstrated the applicability of the data mining method to setting fault interconnection protection for multiple DGs operating on the same distribution feeder. All DGs were found to trip, as they should, for area-EPS faults. The functions of fault type identification implicated faulted phases were also retained for all the implicated DGs.

Chapter 6

Hardware in Loop Application

The Decision Tree (DT) classifiers obtained for both shunt fault detection and recording duties, fully determining the Intelligent Relay settings in terms of both protection handles and thresholds can be easily programmed/implemented within typical industry microprocessor-based over-current relays. Furthermore, the relatively simple structure of the resulting DTs, be it for a single or multiple DGs, make this implementation a relatively uncomplicated task, the only limitation being the functionality permitted by the embedded software of the microprocessor relay in question. The microprocessor relay itself with the embedded relay settings can, subsequently, be interfaced within the loop of a Real Time Simulator (RTS) system simulating the system performance on actual "wall-clock", time and verify whether, indeed, shunt fault incidents are detected based on first-cycle DG fault currents information according to the methodology contained in the previous chapters of this thesis.

In order to illustrate the feasibility of this task, the shunt fault detection DTs of the generator GEN-A, which is one of the three generators considered in the three DG system (see Chapters 2 and 5), have been implemented on an actual commercial relay, the SEL-351 relay, and tested using the OPAL-RT simulator environment as a Hardware In the Loop (HIL) application.

6.1 Real Time Simulator

The Real Time Simulator (RTS) executes the simulation at the same rate as actual "wall clock" time [67]. This allows Hardware In Loop (HIL) testing of various controllers and devices, like protection relays, before they are actually used in power grids. In order to achieve this task, the power system is simulated in the RTS and pertinent measurements are passed through its I/O card as output signals to the controllers/devices that are interfaced as hardware. Output from the controllers can then be passed back to the virtually simulated power grid if so desired. This way, the interfaced controller/device interacts with the virtual power grid, during the simulation, in real time. There are two types of HIL testing: "Open Loop" and "Closed Loop". When in open loop mode, the virtual power grid signals are played on the RTS and then passed on to the controller for further processing. The controller cannot, due to the very nature of the open-loop operating structure, pass its output back the power system, meaning that only a one- way communication is established. Open loop testing can be done by either "playing back" the waveform collected during a previous real time simulation or or by performing simulations in real time. In the closed loop operating mode, the controller actively participates with the real time simulations influencing the evolution of the power system simulations by feeding its output back to the RTS. Given that the task addressed here focuses on simple fault detection, no further action is required from the tested commercial relay. Open loop "playback simulations" were deemed sufficient for testing the concept. The events are simulated in Matlab and voltage and current waveforms are recorded at the point of common coupling of the DG. The waveforms are played in the RTS that passes them on to the tested microprocessor relay. The OPAL-RT real time simulator, whose basic hardware is shown in Fig. 6.1, is used in this thesis. It has an analog I/O card at the back that has 16 outputs that can produce +/- 16 V and +/- 10 mA output signals with an accuracy of +/- 5mV [68].

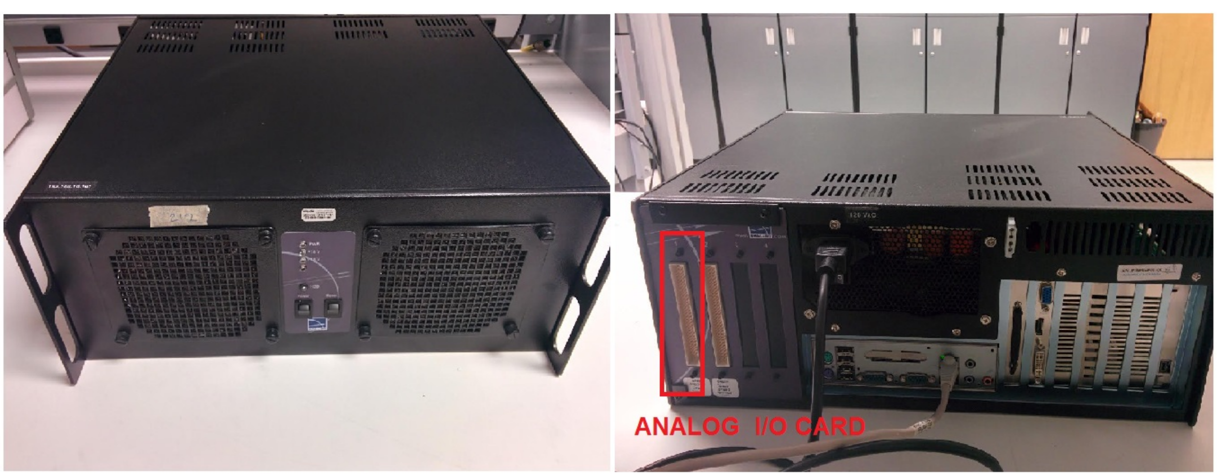

Fig. 6.1 OPAL-RT Real Time Simulator

The OPAL-RT system performs simulations in the Simulink environment using a dedicated API. The HIL Simulink model can be seen in Fig. 6.2. The current and voltage waveforms are calibrated using appropriate scaling multipliers and then passed on to a block that produces voltages at the I/O card level.

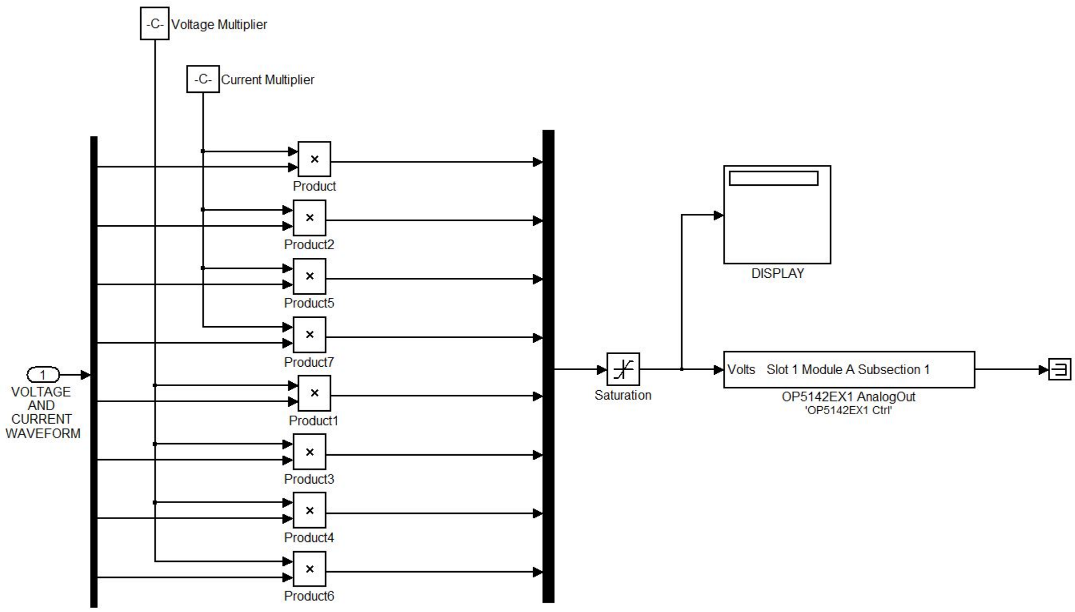

Fig. 6.2 Matlab Model for Generating OPAL-RT Analog Output Values

6.2 Decision Trees Implementation on the SEL-351 Relay

The SEL 351-R is a Recloser Control serving traditional recloser control supervising functions and contains some relaying functionality such as phase and ground directional elements, multiple level under and over frequency trip, and metering [69]. Therefore, when field-commissioned, it takes current inputs from Current Transformers (CTs) and voltage inputs from Potential Transformers (PTs). The inputs are converted to analog signals, normalized to 1 A, before they are actually used by the micro-processor. The analog outputs from the OPAL-RT are fed directly to the microprocessor because OPAL-RT circumvents completely the physical presence of both CTs and PTs. A voltage analog value of 0.5 V is supplied to have 25kV grid voltage with PT ratio of 500 and 0.2 V to have a current of 100 A with CT ratio of 50. It should be noted that these CT and PT ratios simply serve the functionality of this particular implementation and are, thus, not representative of the typical ratios in industrial practice. For the sake of illustration of the concept, the four DTs used by the DG-A fault interconnection protection to detect shunt feeder faults are reproduced in Fig. 6.3 from Chapter 5. They pertain to the case where the DG-A transformer interconnection is Delta-Yg connected and it is these DTs that were implemented/programmed within the SEL-351 relay for further testing.

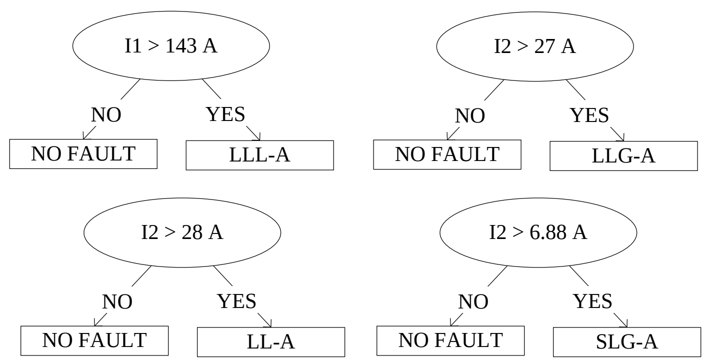

Fig. 6.3 The Fault Detection Decision Trees Implemented on the Relay

The instantaneous phase overcurrent (50P) and negative sequence (50Q) relay elements have been used to program the DTs in the SEL relay and embed them in its functionality, through the SEL-AcSELerator QuickSet program available for configuring the relay. The 50P element triggers when the sensed RMS first-cycle current exceeds its threshold. Similarly, the 50Q element triggers when the negative sequence current magnitude is higher than 3 times its corresponding threshold value. The SEL relay is configured to trip, i.e to flag out that a shunt fault has been detected, whenever either one of its 50P or 50Q elements triggers. The trip logic is provided, schematically, in Fig. 6.4.

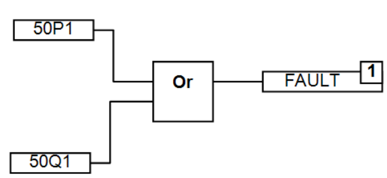

Fig. 6.4 SEL 351R Fault Detection Logic Diagram

During RTS testing, this relay is monitored using also the AcSELerator QuickSet software through Human Machine Interface (HMI) and event history.

6.3 Hardware-in-Loop Results

The HIL application was demonstrated for six different events described in Table 6.1. These events include all four types of shunt faults and two non-fault events. These fault events have different fault resistances and are applied at different locations in the feeder to avoid loss of generality.

Event	Fault Detected
LLL Fault $R_{arc} = 1\Omega$ at Bus 5	Yes
LL - AB Fault $R_{arc} = 1\Omega$ at Bus 13	Yes
LLG - ABG Fault $R_{arc} = 2\Omega$ and $R_g = 0\Omega$ at Bus 13	Yes
SLG - AG Fault $R_g = 40\Omega$ at Bus 12	Yes
Load Connection	No
Normal System	No

Table 6.1 Different Testing Events for HIL application

The system phase voltage (phase to neutral) and current waveform at the DG Interconnection protection location of DG-A (25 kV utility-side of the DG-A dedicated interconnection transformer) are recorded using the AcSELerator QuickSet software. These waveforms can be seen in Fig. 6.5 to Fig. 6.8. The relay processed the raw waveform and provided filtered data, i.e. first-cycle symmetrical RMS phase voltages and currents. These values were passed to the pre-processing blocks and the appropriate quantities needed by the programmed DTs were passed on to the SEL relay. All the fault events have been detected by the relay successfully.

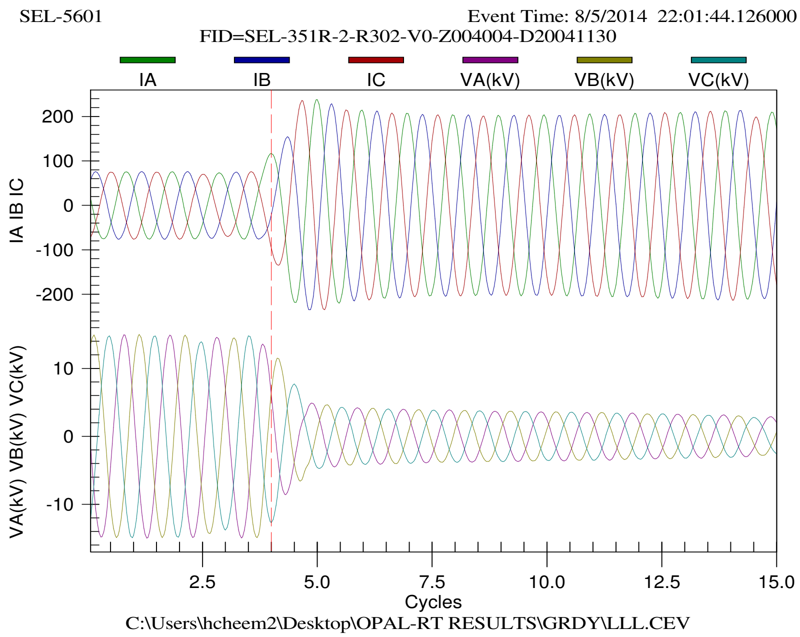

Fig. 6.5 The LLL Fault Waveform Recorded by the Relay

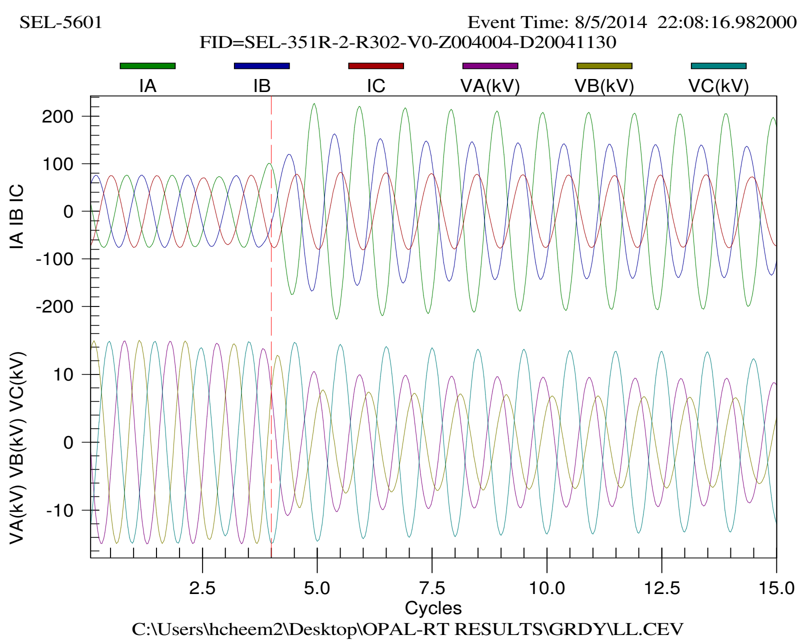

Fig. 6.6 The LL Fault Waveform Recorded by the Relay

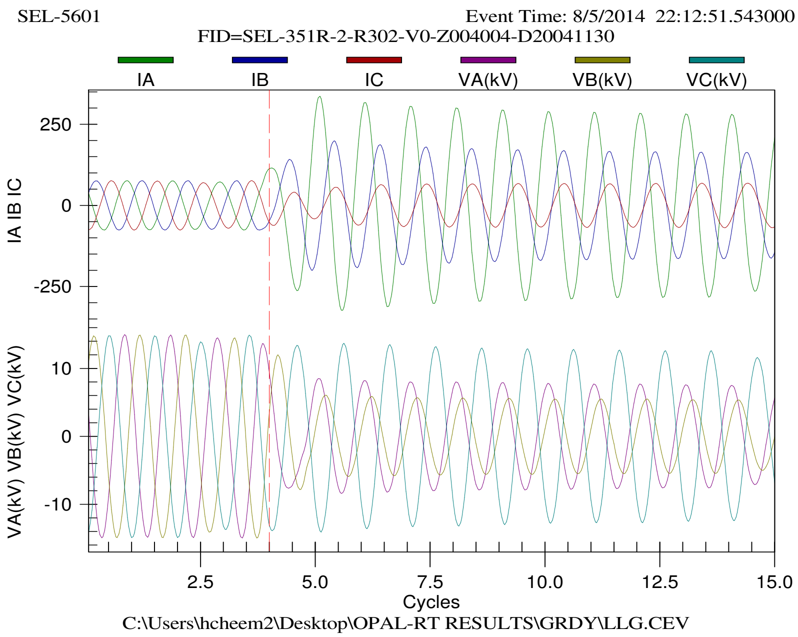

Fig. 6.7 The LLG Fault Waveform Recorded by the Relay

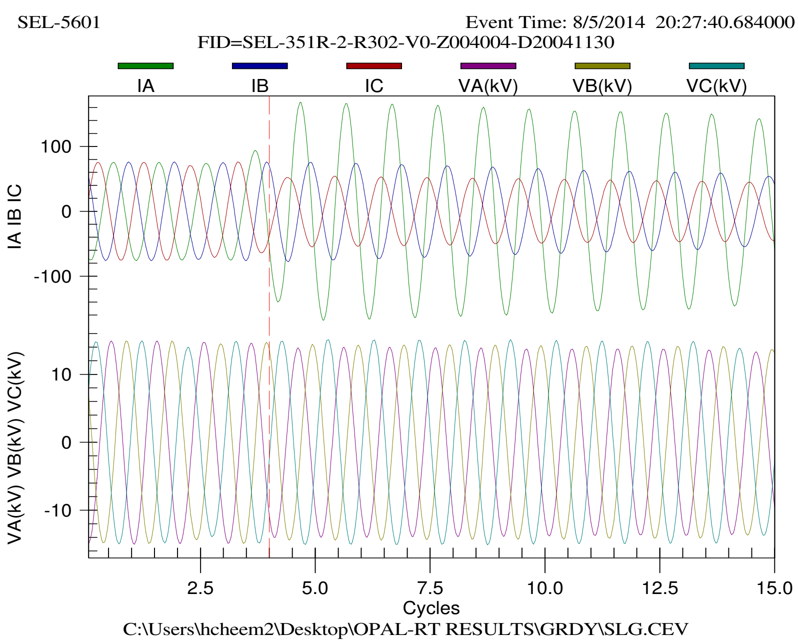

Fig. 6.8 The SLG Fault Waveform Recorded by the Relay

6.4 Conclusions

This chapter has demonstrated that the relay settings obtained by means of data mining algorithms and implemented in the logic of a commercial relay can properly detect faults in a real-time environment. This test was carried out by playing back the faulted system waveforms as obtained by off-line simulations. Identification of the type of fault that was detected by the relay can be implemented in relays that offer recording functions.

Chapter 7

Conclusions and Future Work

7.1 Summary

This thesis described how to set Intelligent Relays (IR), using data mining methods and satisfying a specific set of design requirements, in order for them to be used for area-EPS shunt fault detection as part of a synchronous DG Fault interconnection protection. More specifically:

- The first IR design requirement was that the relay should be capable of detecting all types of shunt faults of various severities, be it symmetrical or asymmetrical, occurring anywhere within the distribution feeder the DG is connected at.
- The second IR design requirement was that the IR should be capable of providing credible fault recording information by properly identifying the shunt fault type and the implicated faulted phase(s).
- The third IR design requirement was that the IR should be equally functional in both its fault detection and recording duties independently of whether the DG Interconnection transformer was grounded, solidly or otherwise, or floated on the utility side.
- The above-stated IR design specifications were used to train an IR using data mining methods in Matlab that yielded simple, interpretable and intuitively acceptable Decision Tree classifiers that encapsulated the required IR tripping logic by virtue of clearly identifying both the protection handles needed as well as their thresholds.

- The applicability of the proposed IR was tested in the Real Time Simulation environment using the OPAL-RT RTS as a Hardware in the Loop application (HIL) using the SEL-351 commercial relay. The commercial relay programmed with the settings obtained using the proposed methodology performed per desired specifications in the RTS environment as well.

7.2 Conclusions

- The performance of the IR was tested on a test-bench distribution feeder and was found to be entirely satisfactory for area-EPS fault detection, of wide varying fault severity, duty exhibiting very reliability.

- The consistently superior performance of the IR versus the performance of conventional protective devices used for fault detection was ascertained for either one or several DGs on the same feeder and irrespective of the DG transformer interconnection.

- The IR relay, set according to the proposed methodologies, proved superior to conventional protective devices in detecting high-resistance/end-feeder ground faults.

- The IR, set according to the proposed methodologies, proved worthy for fault recording duty since it provided credible information, at a quite high success rate, in identifying both the shunt fault type as well as the involved system phases, be it mounted on a single or multiple DGs and for any DG transformer interconnection

7.3 Recommendations for Future Work

The work described in this thesis meant to illustrate the applicability of data mining methods to set relays for Fault Interconnection protection, based on minimal amount information, i.e. first-cycle fundamental frequency quantities. That is why only area-EPS shunt fault events and fundamental non-fault system events were used in the training sets. The work described here could be extended examining the applicability of these methodologies to:

- Examine the possibility of having IRs discriminating between area-EPS faults and transformer inrush phenomena in the absence of directional sensing and/or low voltage DG-side faults .

- Examine the possibility of applying these methods to identify high-resistance faults taking into account the nonlinear behavior of the implicated arc.

- Extending the applicability of these methodologies to changing distribution feeder configurations thus providing a series of adaptive IR settings for different exploitation scenarios.

- Examine the applicability of the proposed approach to set IRs for DGs of a different technology vintage, e.g. inverter-based DGs.

- Examine the possibility to apply these techniques to lower voltage systems where rotating load infeed may also need to be considered as well as load unbalances.

Appendix A

Distribution Feeder Data

A.1 Single DG Distribution System

The substation has short circuit level of 1000 MVA and X/R ratio of 10. It feeds the 25 kV four wire multi-grounded distribution system through a 15 MVA, 114.3 kV/24.94 kV $\triangle/Yg$ transformer. The 25 kV distribution system has total demand of 11.064 MW and 2.345 MVAr. A 1.2 MVAr capacitor is present near the feeder end. A 5 MVA 4.16 kV synchronous generator supplies 30% of the system load in addition to auxiliary load of 250 kW. The DG operates in power factor control mode and maintains 0.95 lagging power factor at the PCC. It is connected to the distribution system through a 12 MVA, 25 kV/4.16 kV $\triangle/Yg$ transformer. The benchmark distribution feeder can be seen in the Fig. A.1.

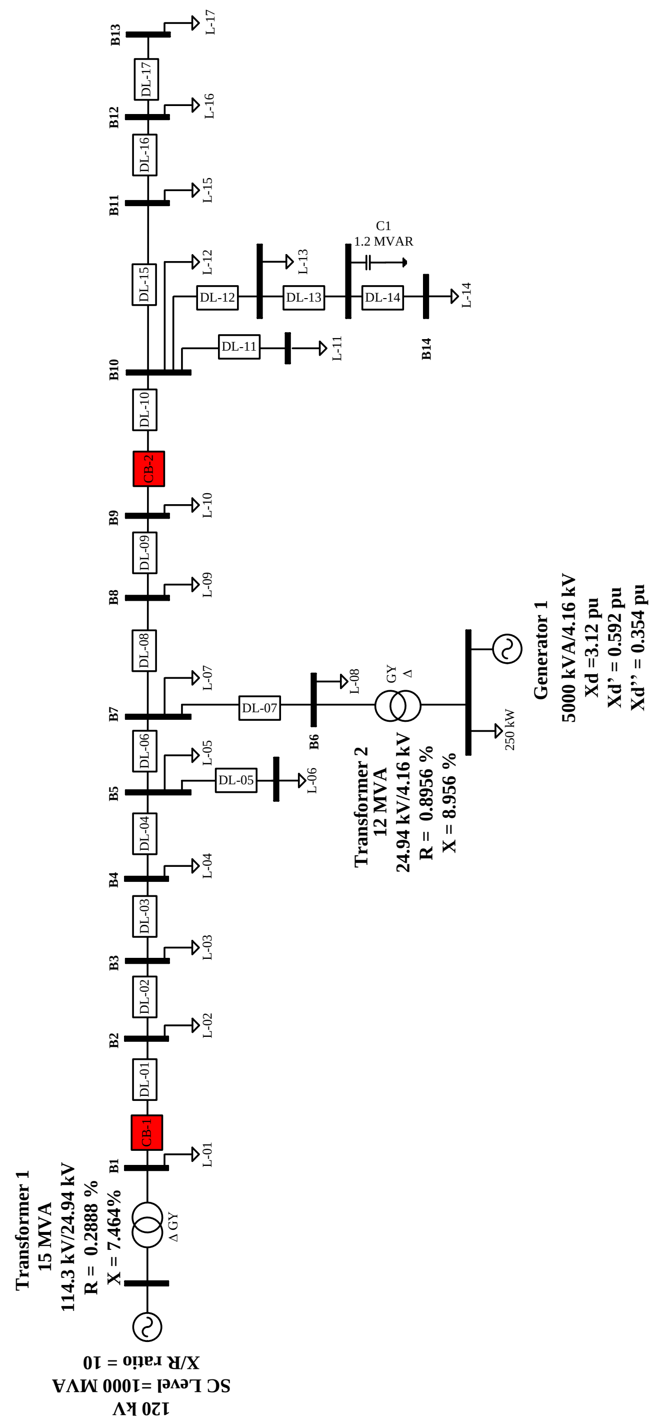

Fig. A.1 Reduced Single DG Feeder Model

The synchronous generator, transformer 1 (substation transformer), and transformer 2 (interconnection transformer) parameters can be seen in the Table A.1.

	Base	Data
Utility Source	$S_{\text{base}} = 10$ MVA $V_{\text{base}} = 114.30$ kV $Z_{\text{base}} = 1306.45\ \Omega$ $I_{\text{base}} = 50$ A	$R = 0.0011$ pu $X = 0.0110$ pu
Transformer 1	$S_{\text{base}} = 10$ MVA $V_{\text{base}} = 114.30$ kV $Z_{\text{base}} = 1306\ \Omega$ $I_{\text{base}} = 50$ A	$R = 0.0020$ pu $X = 0.0498$ pu
Transformer 2	$S_{\text{base}} = 10$ MVA $V_{\text{base}} = 24.94$ kV $Z_{\text{base}} = 62\ \Omega$ $I_{\text{base}} = 232$ A	$R = 0.0075$ pu $X = 0.0746$ pu
Generator 1	$S_{\text{base}} = 10$ MVA/pu $V_{\text{base}} = 4.16$ kV $Z_{\text{base}} = 1.73\ \Omega$ $I_{\text{base}} = 1388$ A	$X_{\text{d}} = 6.2400$ pu $X'_{\text{d}} = 1.1840$ pu $X''_{\text{d}} = 0.7080$ pu $X_{\text{q}} = 4.2400$ pu $X''_{\text{q}} = 0.7080$ pu $X_{\text{l}} = 0.2080$ pu $R_{\text{s}} = 0.0144$ pu $H = 1.0700$ s

Table A.1 System Components' Per Unit Data

Table A.2 shows the distribution lines data.

	R1 (Ω/km)	R0 (Ω/km)	L1 (mH/km)	L0 (mH/km)	C1 (nF/km)	C0 (nF/km)	Line Length (km)	X/R Ratio
DL-01	0.114	0.377	1.030	3.450	1.000	1.000	4.167	3.410
DL-02	0.116	0.384	1.050	3.510	11.500	4.810	2.291	3.410
DL-03	0.116	0.384	1.050	3.510	1.000	1.000	2.040	3.420
DL-04	0.116	0.382	1.040	3.490	1.000	1.000	6.517	3.390
DL-05	1.469	1.469	3.650	3.650	1.000	1.000	0.970	0.940
DL-06	0.113	0.375	1.020	3.430	12.700	7.750	15.000	3.390
DL-07	0.116	0.384	1.050	3.510	11.500	4.810	10.670	3.410
DL-08	0.113	0.375	1.020	3.430	1.000	1.000	1.590	3.390
DL-09	0.116	0.384	1.050	3.510	11.500	4.810	0.452	3.410
DL-10	0.116	0.383	1.040	3.500	1.000	1.000	1.050	3.390
DL-11	0.328	0.597	1.170	3.650	1.000	1.000	0.170	1.350
DL-12	0.286	0.529	1.050	3.280	1.000	1.000	1.210	1.380
DL-13	0.851	1.211	1.340	4.150	9.320	4.400	0.194	0.590
DL-14	0.851	1.211	1.340	4.150	9.320	4.400	0.106	0.590
DL-15	0.244	0.497	1.070	3.390	1.000	1.000	0.423	1.660
DL-16	0.265	0.482	0.946	2.940	1.000	1.000	2.910	1.350
DL-17	0.424	0.670	0.933	2.970	1.000	1.000	5.450	0.830

Table A.2 Distribution Lines Data

The system load data is presented in the Table A.3.

	Active Power (kW)	Reactive Power (kVAR)
L-01	507	99
L-02	297	62
L-03	18	2
L-04	532	97
L-05	612	110
L-06	60	6
L-07	452	98
L-08	60	14
L-09	37	4
L-10	610	127
L-11	1866	394
L-12	29	6
L-13	605	162
L-14	1185	240
L-15	1718	338
L-16	1868	571
L-17	608	13
Total	11064	2345

Table A.3 Load Data

A.2 Three DG Distribution System

The multiple DG distribution system is same as one presented in the last section but has two additional generators. The Gen A is same as single DG distribution system and is studied under delta and solid grounded interconnections to the utility. The Gen B is a 3 MVA generator that is connected to the utility with impedance grounding. And, the Gen C is a 4.5 MVA generator connected to the utility with delta interconnection on the utility side.

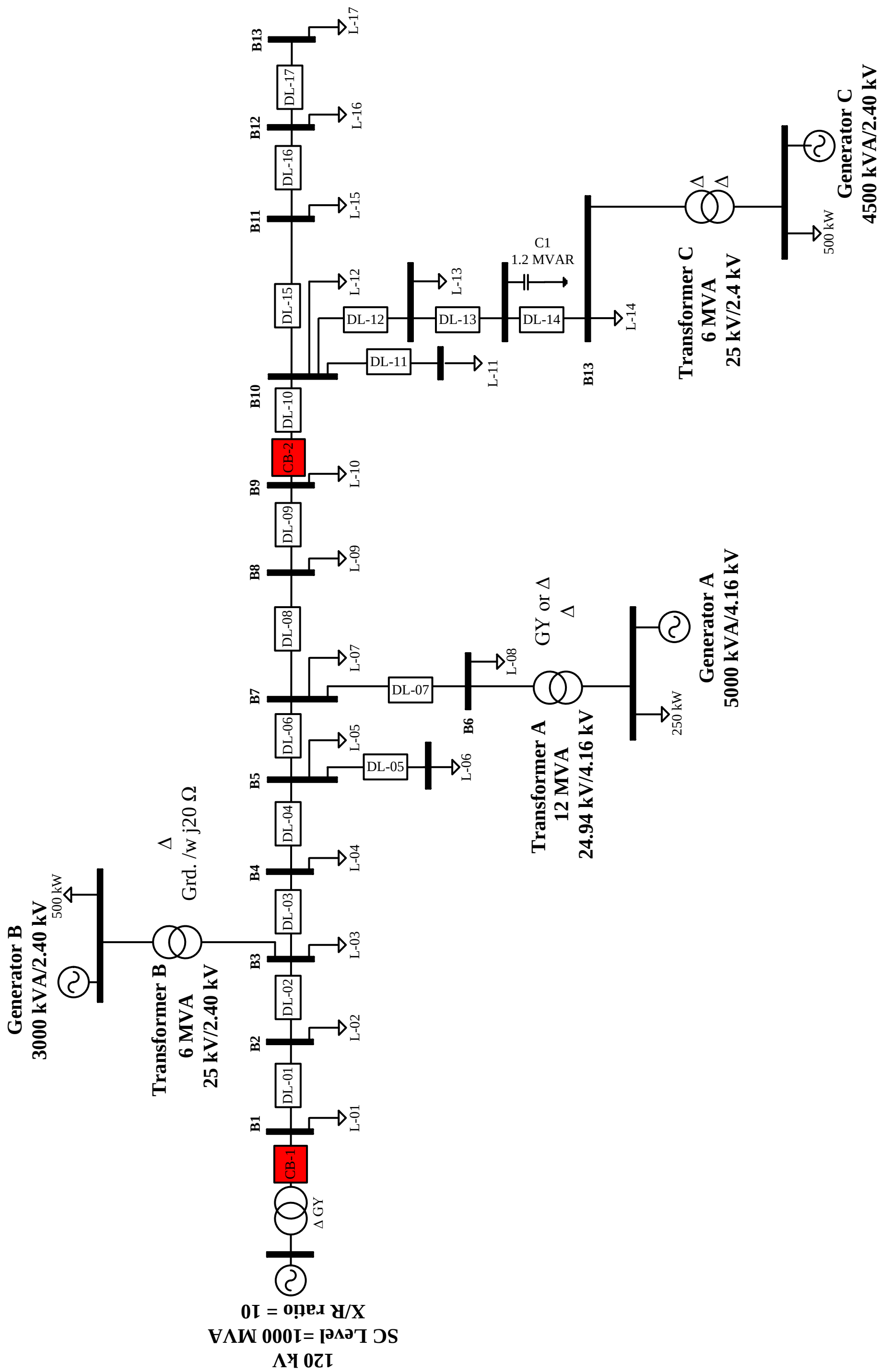

Fig. A.2 Multiple DG Distribution System.

The Gen-B and Gen-C parameters are provided in the following.

	Base	Data
Transformer B	$S_{\text{base}} = 6$ MVA $V_{\text{base}} = 25$ kV $Z_{\text{base}} = 104.2\ \Omega$ $I_{\text{base}} = 138.6$ A	$R = 0.00453$ pu $X = 0.0453$ pu
Gen - B	$S_{\text{base}} = 3$ MVA/pu $V_{\text{base}} = 2.4$ kV $Z_{\text{base}} = 1.92\ \Omega$ $I_{\text{base}} = 722$ A	$X_{\text{d}} = 1.56$ pu $X'_{\text{d}} = 0.3$ pu $X''_{\text{d}} = 0.2$ pu $X_{\text{q}} = 1.06$ pu $X''_{\text{q}} = 0.18$ pu $X_{\text{l}} = 0.052$ pu $R_{\text{s}} = 0.0036$ pu $H = 1.0700$ s
Transformer C	$S_{\text{base}} = 6$ MVA $V_{\text{base}} = 25$ kV $Z_{\text{base}} = 104.2\ \Omega$ $I_{\text{base}} = 138.6$ A	$R = 0.00452$ pu $X = 0.0452$ pu
Gen - C	$S_{\text{base}} = 4.5$ MVA/pu $V_{\text{base}} = 2.4$ kV $Z_{\text{base}} = 1.28\ \Omega$ $I_{\text{base}} = 1082$ A	$X_{\text{d}} = 1.56$ pu $X'_{\text{d}} = 0.3$ pu $X''_{\text{d}} = 0.2$ pu $X_{\text{q}} = 1.06$ pu $X''_{\text{q}} = 0.18$ pu $X_{\text{l}} = 0.052$ pu $R_{\text{s}} = 0.0036$ pu $H = 1.0700$ s

Table A.4 Multiple DGs Per Unit Data

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