Renewable and Sustainable Energy Reviews 46 (2015) 129–142

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Technical challenges for electric power industries with implementation of distribution system automation in smart grids

Kashem M. Muttaqi [a], Jamshid Aghaei [b,*], Velappa Ganapathy [c], Ali Esmaeel Nezhad [d]

[a] Australian Power Quality and Reliability Centre, School of Electrical, Computer and Telecommunications Engineering, University of Wollongong, Wollongong, NSW, Australia
[b] Department of Electrical and Electronics Engineering, Shiraz University of Technology, Shiraz, Iran
[c] Department of IT, Faculty of Engineering & Technology, SRM University, Kattankulathur 603203, Chennai, India
[d] Department of Electrical Engineering, Marvdasht Branch, Islamic Azad University, Marvdasht, Iran

ARTICLE INFO

Article history:
Received 22 October 2013
Received in revised form
9 August 2014
Accepted 7 February 2015

Keywords:
Distribution system automation
Smart grids
Renewable energy
Demand side management
Distributed generation

ABSTRACT

Recent improvements in computer processing power have enabled the development of intelligent electronic devices (IEDs) to be capable of interpreting a substantial quantity of data at high speeds. The distribution industry is one of the largest users of real-time data during the operation of their energy distribution network and as such, has an inherent need for data processing technology. The development of intelligent devices and communication protocols has given rise to the concept of distribution system automation (DSA). In this paper the major features of DSA development are discussed. A method of communication along with the integration of wired and wireless communication solutions with IED and Mote technology is described. Protection scheme automation is investigated, showing that automated response to network fault conditions is possible. Network reconfiguration is another key aspect of DSA research and two distinct calculation techniques are discussed. The current index (CI) and the load balance index (LBI) calculation methods are presented and the benefits of LBI are highlighted. Distributed generation (DG) is addressed in the context of automation with a demand side management (DSM) program proposed to manage load during peak and off-peak periods. The paper discusses switching DG sources, load deferral strategies and direct load control to effect a reduction in load during peak periods. The paper furthers this load management by load filling during off-peak periods. Finally, conclusions on the effectiveness of the proposed method are drawn and recommendations are made for further research.

Contents

* Corresponding author. Tel.: +98 711 7264121; fax: +98 711 7353502.
E-mail address: aghaei@sutech.ac.ir (J. Aghaei).

http://dx.doi.org/10.1016/j.rser.2015.02.013
1364-0321/

1. Introduction

The institute of Electrical and Electronic Engineers (IEEE) has defined DSA as a system that enables an electric utility to remotely monitor, coordinate and operate distribution components in a real-time mode from remote locations [1]. Utilities have realised that the traditional control method is out-dated with the possibility of establishing true automation of the network [2]. Full automation of the energy distribution system is possible due to the advances in data processing technology and telecommunication systems [3]. There are many reasons as to why DSA development is increasing in the focus of distribution utilities. Advances in technology production (IED) reduce technology production costs [2] and improve computer chip processing power. Merits of the automated system over the supervisory system, competitive market forces related to deregulation [2], and legislation, are the major driving forces behind the development of DSA across the world as shown in Fig. 1. As this figure shows, there are several factors that cause the conventional power distribution systems to move towards automated systems. From the economic point of view, restructuring power systems and new emerging electricity markets besides the reliability and security issues forces the evolution to intelligent networks, while aging work forces and infrastructure make this procedure much faster. Another factor influencing this process is the advances in technology, which can considerably improve the environmental issues. From the political viewpoint, the exhausting oil reserves and limitations of energy supply in addition to increasing demand cause the conventional distribution networks to be replaced with the new intelligent ones.

The implementation of DSA requires the installation of many new devices and systems. This action may cause many problems for utilities during the progression from the old technology to the new automated technology and systems. Utilities have already installed the new devices, communication systems, software and hardware, and developing protocols and business systems to maximise DSA [3]. The following items focus on communication, protection and network reconfiguration and propose possible solutions to the implementation of these key aspects of DSA.

1.1. DSA technologies and current status

There is a perceived need by energy distribution companies across the world to shift away from current supervisory control systems towards full automation. This section is mainly concerned with the current status of DSA technology, its research and implementation across energy distribution networks while the main issues of DSA, communication, protection and network configuration are discussed.

1.1.1. DSA technologies

The communication systems that are essential to DSA provide many challenges to the implementation of the technology. The

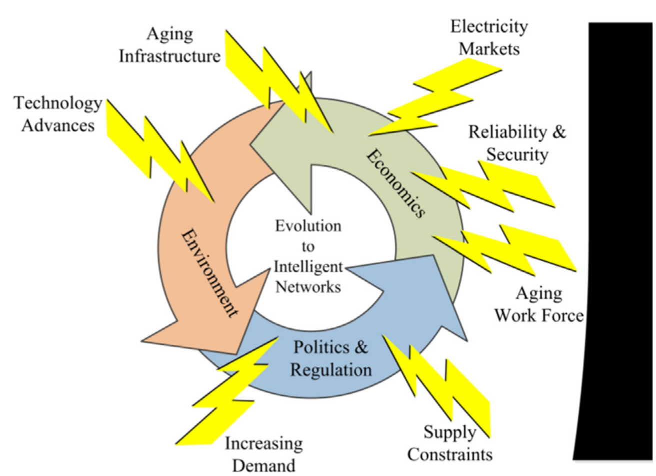

Fig. 1. Drivers of DSA.

communication systems used for supervisory control were suitable for the technology at the time of supervisory control and data acquisition (SCADA) installation, but with the technological advances in recent decades, it has become evident that a more effective communication system should be established for DSA.

1.1.2. Current systems

Energy distribution utilities all across the world are currently controlling their distribution network using supervisory control techniques commonly known as SCADA. SCADA is a centralised controlling system that involves a system operator to use available data in decisions relating to the control of the distribution network [3]. Distribution systems need a new protection, control and operation theory for dealing with new emerging challenges to well implement the smart grid idea [4]. SCADA systems would a vital component for this end [5,6]. In this regard, the SCADA systems previously employed in the higher levels of power systems to send/receive measurement data, status information and control signals to/from remote terminal units (RTUs) must be replaced by newer systems to meet the requirements of smart grids [7]. The conventional SCADA systems use a closed operating environment. In such SCADA systems, maximizing the functionality is the main issue while the security issues are of low priority. This means that the conventional SCADA networks are not robust in the case of security [2,8,9]. From the competitive market point of view, industries have to enhance their SCADA systems to raise the efficiency and reduce the costs. Therefore, SCADA systems are moving towards open access networks [10]. This significant issue makes such systems to be potentially exposed to interruption of services leading to disruption of infrastructures and industries [8,10]. Consequently, the security level of the SCADA systems is a key point which is still controversial [11].

Some features are automated in this instance but do not strictly adhere to system automation. For example in fault conditions, the feeder's protection automatically operates to isolate the fault from the rest of the network, but it then requires another operator to travel to the affected feeder and determine the next course of action [3]. The manual investigation of the faulted section and the dispatching of crews to the affected section would be done automatically with DSA and a minimal number of customers will be affected.

For DSA to be achieved, it requires a communication medium for which, the intelligent devices can communicate through. This is to ensure that intelligent devices have all possible real time state values of the distribution network so that, the devices can make an accurate decision [3]. This has been one of the major issues with DSA implementation as there are many theories as to which method(s) is the most cost-effective and produces the best outcome for a DSA system. Like all communication systems, they can be either wired or wireless.

Each system has issues and benefits over the other ones. During an ideal implementation of DSA, a wired network made from the best materials would be installed as the intermediate through which communication is achieved. In reality it is envisioned that, a combination of the two methods would be employed [12]. This might be due to long distances for communication encountered in remote communities, where load density is the lowest and therefore, the installation of wired communication would not be cost-effective. Possible solutions for wired communication systems include optical fibre, power line carrier (PLC) and existing national telecommunication networks, whilst wireless transmitter/receiver pairs and satellite technology are of possible wireless solutions.

These are some solutions that are currently being investigated and trailed while they all have advantages and disadvantages over each other. It is noted that a combination of all these processes would form a part of the whole DSA solution in any given Distribution company's network as illustrated in Fig. 2.

1.1.3. Communication method

Fundamental to DSA systems is how the devices communicate with each other. One theory is to use a combination of peer-to-peer technology with a centralised system. Centralised control uses a network operator to oversee all actions that the system automation performs with communications going through this central command as well as the devices communicate directly to each other [12]. This is to ensure that should the automated

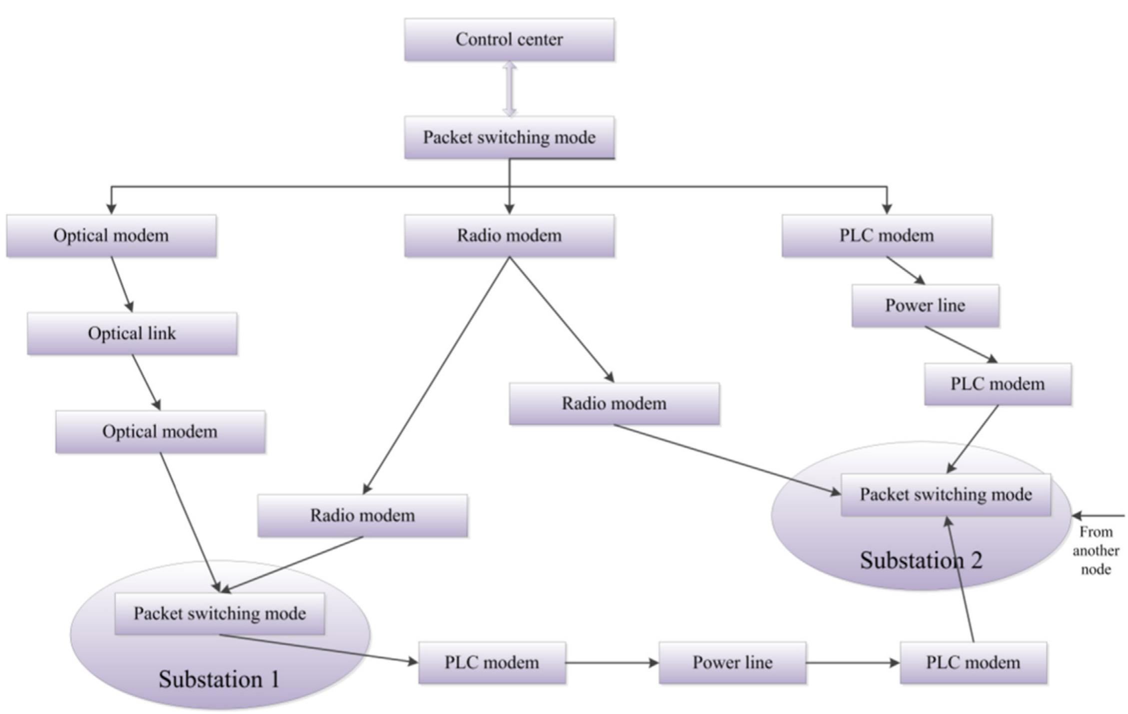

Fig. 2. Possible DSA solution [13].

system need an override due to unforeseen circumstances, then this action is possible.

The intelligent devices measure, record and communicate local network status indicators to their peers. This enables remote devices to make automated decisions of local and global network status indicators, therefore providing the best possible automated response.

1.2. System fault and automation

When a fault occurs on a feeder, the normal system protection will be set off locking out the feeder from the source. The logical intelligent devices decide where the fault has occurred through the communication between each other and decide the best course of action relating to the programmed logic. This process should either isolate the fault and return unaffected customers to service or return all customers to service depending on the type of fault [12]. The obvious benefit is the speed at which this would be done as opposed to the current practice of manual and supervisory operation of such features.

Fig. 3 depicts a section of network, wherein there is a fault on a section of feeder at load 7. The automated response is delivered by the communication links shown as the dotted lines in the diagram forcing switches 6 and 9 to open. This isolates not only that section of the faulted network from the rest of the system, but also the unaffected load 5. To remedy this problem and return load five to service, the normally open switch 7 is closed temporarily until the fault is cleared.

1.2.1. Exceeding rated specifications

DSA can monitor network equipment to ensure that neither they get overloaded nor operate at a higher temperature than specified [12]. If any such problems eventuate, then load shedding can automatically occur to protect equipment. Some loads, such as hospitals cannot and should not be shed in these situations. So provision for this situation is built into the logic of DSA load shedding feature. The reverse of load shedding can also be achieved as the situation returns to normal allowing more load to be reconnected to the source.

1.3. Network reconfiguration

The most important controllable system features with regard to network configuration are load management, load shedding, voltage regulation, VAr regulation, power factor correction, automated meter reading and data collection. The control of these system aspects provides the benefits of reduced system losses, higher efficiency, reduced operational costs and improved power quality (PQ).

1.3.1. Load management

During the day, the load profile fluctuates from base-load levels to peak-load demand which can cause great stress on the system [14]. The network must be able to handle the peak-load demand, even though it occurs only for a fraction of the day which means that the network is highly underutilised. Additionally to this fact is that a

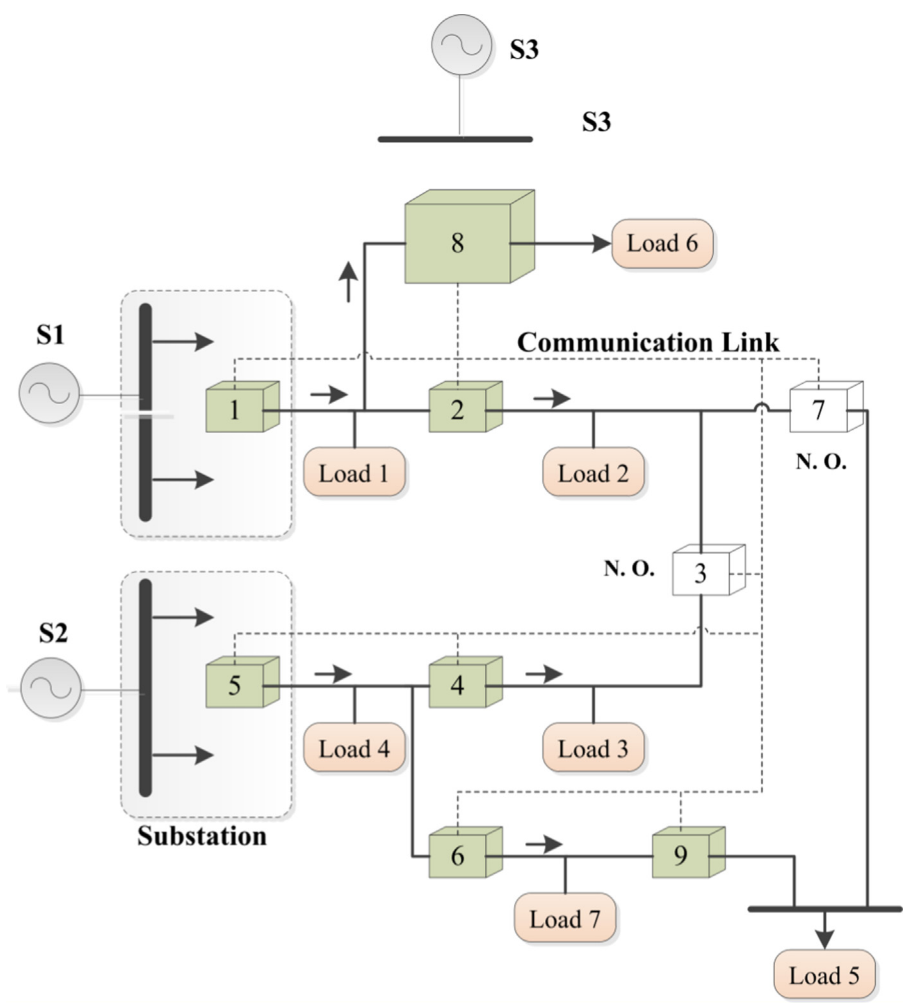

Fig. 3. Example of DSA network [12].

feeder's peak loading can occur at different times to other feeders causing feeder unbalance. Rearranging the network to re-balance it is one possibility that DSA enables distribution companies to achieve higher efficiency in operation and lower losses on the network that both of which translate into lower operational cost [12].

Fig. 4(a) shows the normal configuration of the example network. Through DSA, the system has detected the overloading of the primary source. Fig. 4(b) indicates all possible switching configurations in an open position. This diagram is merely to show the possibilities of switching as a benefit of DSA to avoid any customers' interruption. Finally the situation is rectified through the appropriate switching of loads to parallel sources as shown in Fig. 4(c).

These processes can be automated to suit the real time situation of the distribution network. As a consequence of automated voltage control, VAr regulation and power factor correction, the network experiences lower system losses and delivers better power with higher quality to the end-users [16]. Furthermore, the lifetime of all tap changing equipment is extended due to fewer operations and therefore, less maintenance which defers asset replacement sometimes indefinitely again leading to lower costs [16].

1.3.2. Automated data collection

Data from the network could be read automatically for planning purposes using DSA systems [17]. Maximum demand indicator (MDI) data could be read automatically from distribution substations and even a 15-min demand profile could be obtained, if it is needed. Data collection such as above example has a very important application to planning system alterations and expansions due to load growth. In addition to MDI reading automation, customer's energy consumption could be read and monitored, remotely. This would simplify the billing process and also prevent the electricity theft and fraud [17].

The benefits of DSA to both business and avoiding any the consumer vast outage outweigh the cost of implementation and therefore, the faster the industry moves towards full DSA which is more beneficial to everyone [18].

2. Status and trends of DSA technologies

The basis of the DSA network is IED. These intelligent devices monitor and record the status of the local network and have the ability to communicate with other compatible devices. The IEDs collect information on local network status and from other IEDs [19], through Mote devices. Motes are essentially sensory equipment mounted on a small computer that can process the incoming status signals and energy waveforms [20], and also provide additional intelligence for communication. To communicate with each other through the Mote devices, IEDs need a communication channel to send and receive data. The application of IED and the Mote device in conjunction with a composite communication channel consisting of optical fibre, wireless technology and existing telecommunication networks is discussed. This discussion includes the challenges that the diverse Australian energy distribution environment presents and a possible solution is proposed.

2.1. IED and Mote sensory equipment

The technological improvement in data and computer processing has enabled the development of intelligent devices, that can be programmed to perform certain automated tasks under certain network conditions. These IEDs when coupled with input computer sensory equipment, such as Mote devices can perform automated tasks with high efficiency allowing true DSA to be achieved.

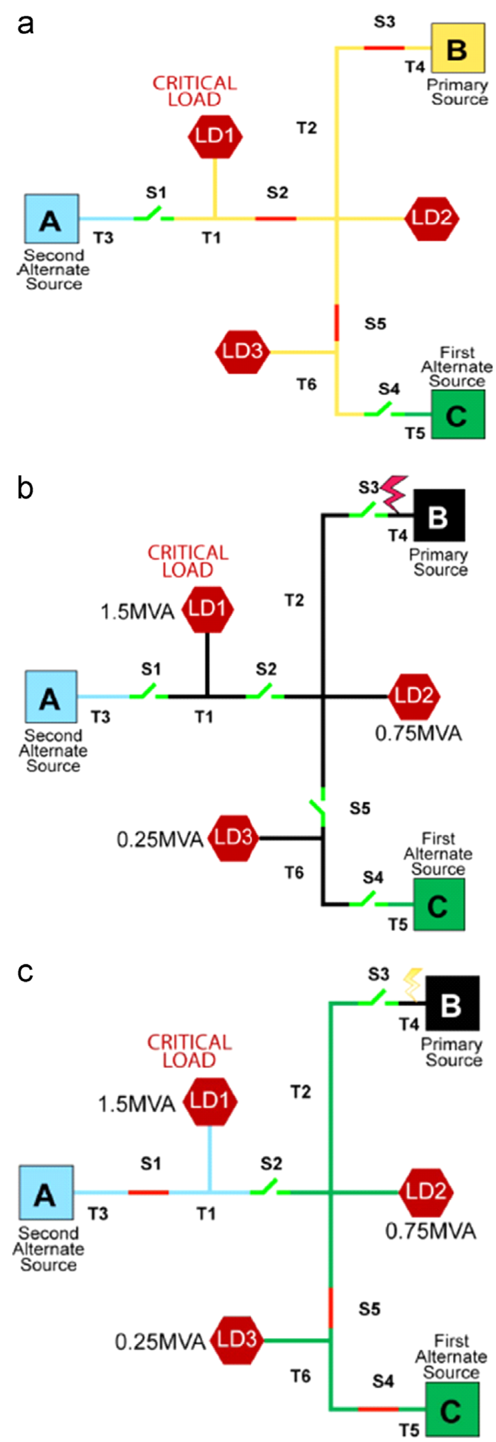

Fig. 4. Network reconfiguration switching possibility [15].

2.1.1. Intelligent electronic device (IED)

The current trend in substation design is to retrofit new IDEs as a part of the monitoring systems of the substation. SCADA achieves limited use of the processing power that these devices possess and as such a movement towards full automation of the distribution system is currently sought to realise the full potential of IEDs.

IEDs are not only essentially digital relays that monitor instantaneous values on the local section of the network, but also contain additional functionality that previous electromechanical relays could not achieve. In addition to the standard instantaneous volts, amps, MW and MVAr, the IEDS can also obtain data on fault event logs, metering values and oscillography (Voltage, current, power waveforms

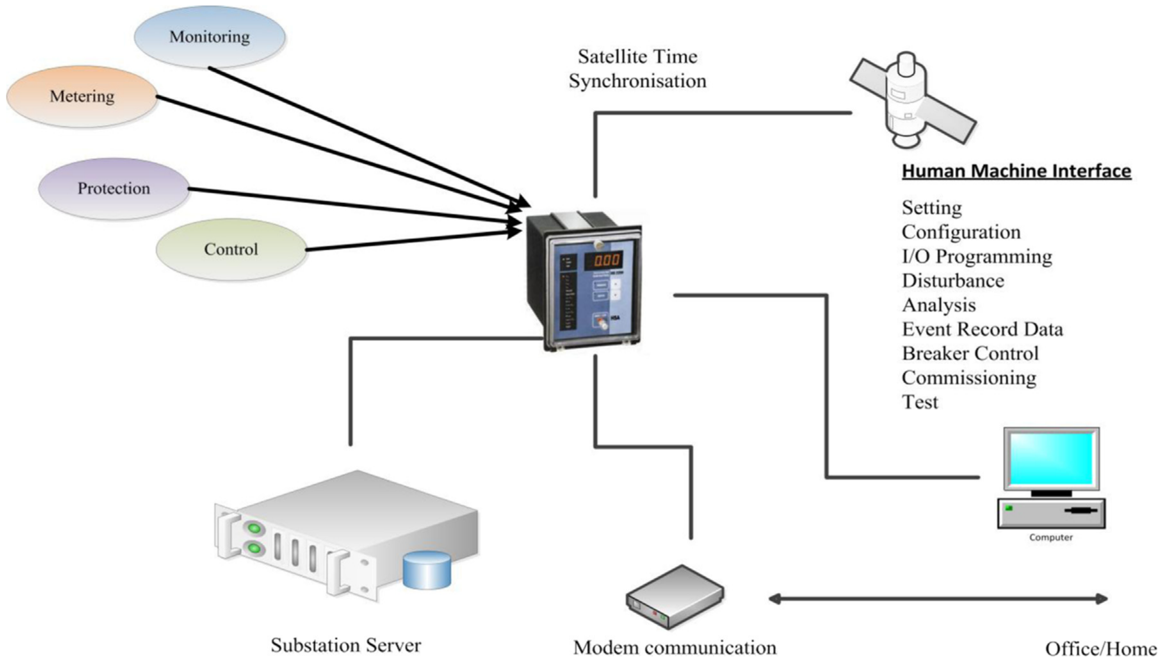

Fig. 5. Substation communication [21].

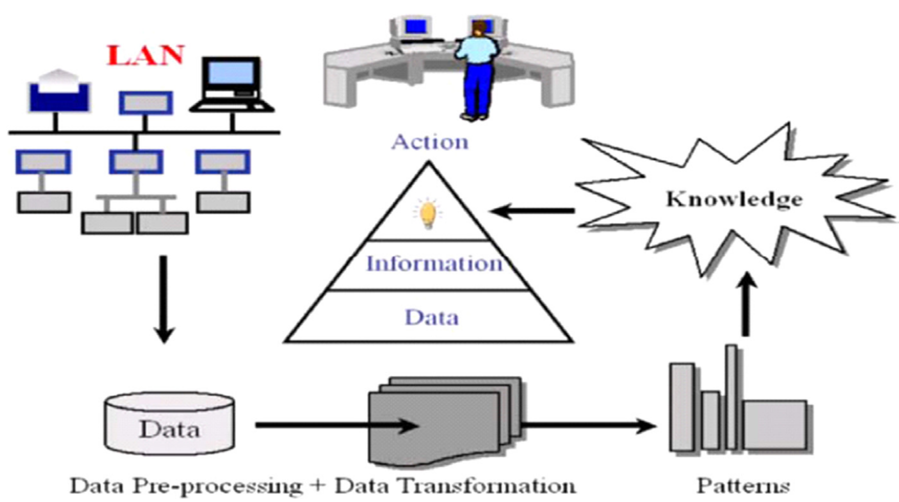

Fig. 6. Information flow [21].

and harmonics) [19]. Due to the added functionality of IEDs, it is a common practice to replace any faulty protection or monitoring relay with an IED relay in anticipation of DSA.

Fig. 5 shows the typical overview of the IEDs functionality. The monitoring, metering, protection and control links are all inputs obtained by the IEDs synchronised via satellite connection to maintain real-time analysis. The substation server stores all the collected data obtained by the IEDs, while the modem simultaneously transmits the data to other IEDs or centralised command for analysis. The computer screen illustrated in Fig. 4 represents the human interaction interface where remote programming, remote control and override, commissioning tests and supervisory activities can be performed [21].

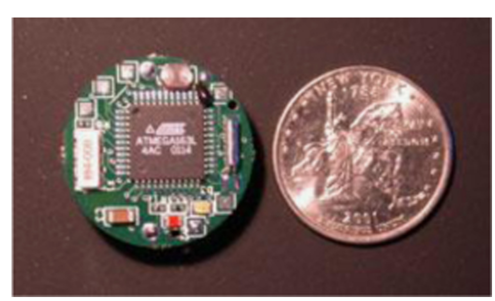

Fig. 7. Mote.

The major problem with IEDs is the vast magnitude of data and information that are collected. Not all this data is useful for control, especially during emergency situations where data collection is generally at its peak. It is during these emergency periods that operators may experience information overload leading to slower and less confident actions, which may possibly be incorrect for the current situation [21]. This is not desirable during any operational period, particularly during emergency conditions when safety could be compromised. This shortfall can be eliminated through the filtration and pre-processing of data, so that only important information is presented to the operator therefore negating the risk of overload.

Fig. 6 demonstrates the information flow from collection through processing and transformations. The processed data is then analysed for specific patterns that may be of interest to the operator and presented for review on which a decision is based [21].

2.1.2. Mote computer sensor nodes

Mote stands for re-Mote computer and consists of sensory equipment mounted on a small computer. The CPU is small compared to today's computing standards, but sufficient to process incoming sensory signals and produce outgoing communication signals for applications, where size is a concern [22], (Motes typically are the size of a 20c coin but some motes have been produced much smaller). Mote allows complex analysis of the immediate network status which is in close vicinity to the mote leading to negating the use of bulky equipment in the space confined situations. Fig. 7 shows a comparison between a mote and a coin in the case of size.

Motes enable the communication of network data to other nodes for consideration. This is accomplished through a wireless transmitter and antennas that motes possess in association with a specific communication protocol allowing efficient communication between mote nodes [20]. Motes can be mass produced to provide a cheap means of achieving this outcome making the technology attractive for distribution companies requiring DSA implementation [22].

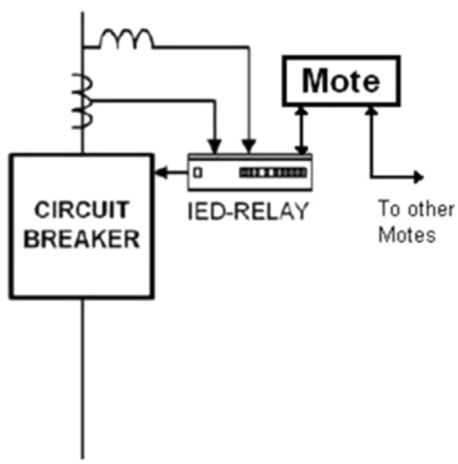

Fig. 8. IED [21].

In most applications of motes, the limiting factor is their power consumption which is considered the most common dilemma [23]. Since the devices are in remote locations, there are generally powered by batteries and therefore to extend the lifetime of the battery, it is desirable that the device is as efficient as possible [24]. Operating and communication protocols have been written for motes allowing them to 'sleep' when not in use leading to saving power and extending the battery lifetime [20]. In the distribution sense Motes could be continually charged by the energy distribution network until a fault occurs. The Mote would then run off a fully charged battery until power was restored allowing them to remain effective during this time.

2.2. IEDs, Motes and communication

The technology that has enabled DSA to become a viable cost-effective option for distribution companies and the driving forces behind moving towards DSA have ensured that much research has been performed on the integration of the separate units.

2.2.1. Mote and IED interaction

The interaction between the IED and Mote forms the basis for data collection on the network [21]. The IED is a relay collecting all the network status data and waveforms in their raw form and then send this data to the mote. The IED may act upon the information simultaneously, such as when a fault is detected requiring an immediate circuit breaker operation to protect electrical equipment. The mote has the potential to receive instructions in this application to DSA that instructs the IED to perform an operation or to override a performed operation [21]. This instruction could be sent from a centralised command point known as decision support or could be initiated by the mote itself after receiving further network status information from the surrounding motes. Fig. 8 shows the possible interaction between the IED and Mote.

2.2.2. Inter-nodal communication

It is assumed that inter-nodal communication between motes is implemented through peer-to-peer communication means. The mote and available communication connectivity protocol enable peer-to-peer communication systems to be used for DSA [25]. The motes communicate peer to peer through wireless technology

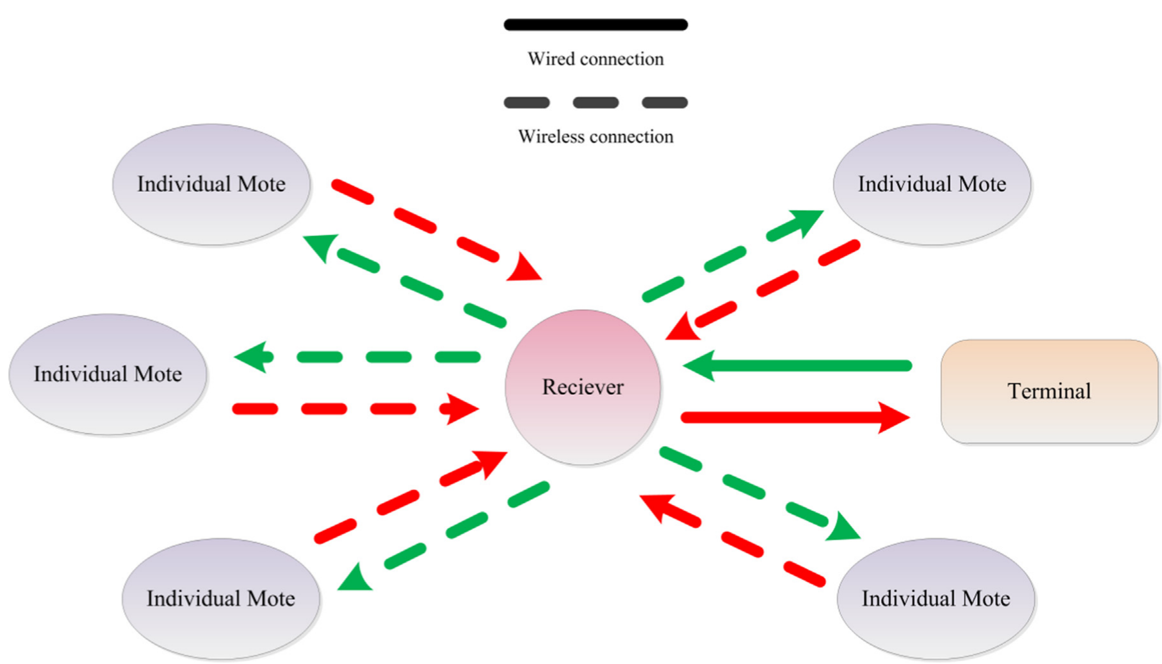

Fig. 9. Substation star topology [26].

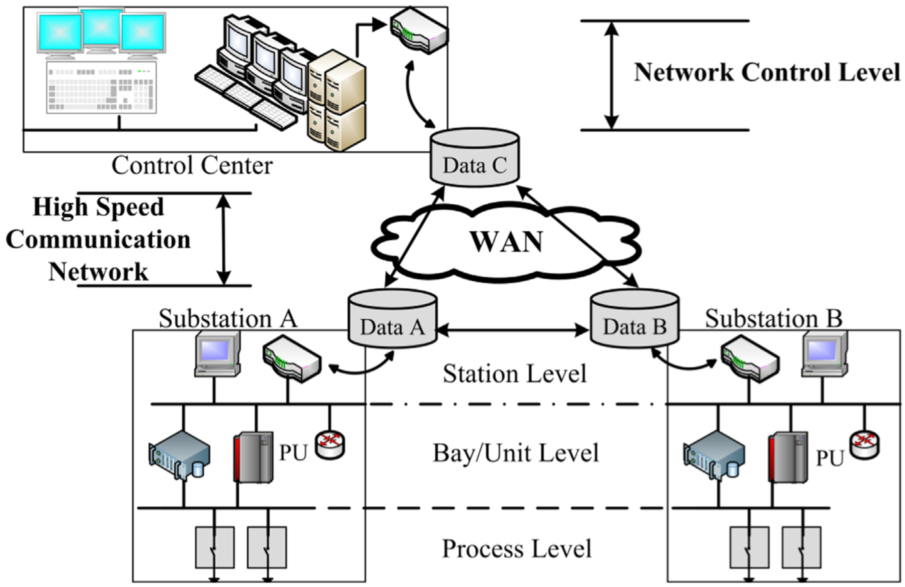

Fig. 10. Communication levels [27].

allowing a number of nodes to converse with each other. The motes exchange data using a centralised receiver as a router, whilst the receiver also acts to process and store information. The receiver or substation server also performs the operation of a gateway to send data to a common substation terminal [26]. Fig. 9 shows a practical application of mote connectivity in a substation using a star network topology.

The terminal unit, then connects to the network's control communication channel which is generally a high speed Wide Area Network (WAN) communication system. This system can also communicate with other substations in the area through their corresponding terminal units, while a centralised decision support command observes the control features of the network ready to interrupt or override any incorrect operations. The centralised decision support can initiate the control signal through this network, or disable a control signal for a multiple purposes. One such example is isolating a section of the network and disabling reconnection to facilitate maintenance work on the system. An operator could remotely switch the network for safe working conditions and also for preventing the intelligent system from restoring supply [27].

Fig. 10 depicts the levels of information propagation from the sensory IED stage at the process level as well as the Mote communication at the Bay/Unit level and the terminal substation unit at the station level. From this point, the data is pre-processed before entering the high speed communication network, where the information can be sent to other substation nodes and the decision support control centre for the operator to analyse. Fig. 11 on the other hand indicates the WAN in action as a peer-to-peer network. From the initialising substation, there are many ways to propagate the information to the control centre and as such the protocols exist for this type of network and to find the fastest way to send information from the source to the sink [25].

2.2.3. Security

Information security across the DSA communication network is important to guard against malicious attack and possible sabotage activity. With parts of the communication network being wireless, this produces an obvious security weakness as any person with correct expertise has the potential to observe and even influence network control. There are many encryption techniques providing some security level, but as with all encryption techniques, there is the associated threat of decoding [28]. For DSA to be successfully implemented on the distribution network, a solid and secure communication network must be developed to mitigate the potential security breaches.

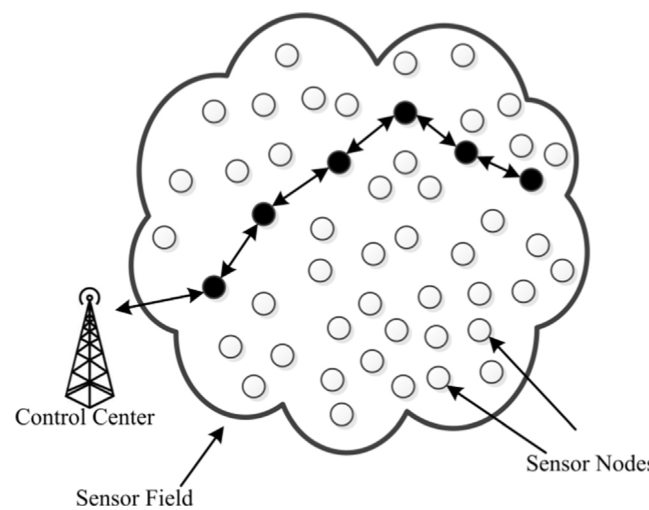

Fig. 11. Message propagation [25].

2.3. DSA in the context of Australia

Recently, Australian distribution companies and in particular, New South Wales (NSW) distribution companies have been undergoing a substantial investment in capital expenditure to improve reliability and cater for additional load growth occurring across the major load centres. Concurrently with the capital investment program, the distribution industry is looking to move towards automation of the energy distribution system and as such, it is investigating the ways of implementing DSA. It must be said that, while investigation into DSA implementation is being carried out, the NSW distribution companies are squarely focused on delivering their extensive capital works program. The followings are a few of the researched concerns that faced by Australian distribution companies as they embark on their DSA journey.

2.3.1. Central business districts (CBDs)

CBD will generally be typified by high load density, short feeders (typically less than 80 km) and strong points of supply. The CBD has a reliable supply of power to customers servicing commercial and residential loads [14]. Because of the importance of keeping these loads connected to supply and the high load density, a reliable communication link between nodes is essential. Optical fibre installations seem to be the best solution to this scenario as large amounts of data can be transmitted across the communications network easily at fast speed through this type of channel [29]. Due to the congested nature of the CBD, there may be a need for wireless solutions to be implemented as options for optical fibre cable installation may be limited.

2.3.2. Regional

Regional scenarios are generally typified by medium load density. These areas can have reliability problems on some sections of the network, lower PQ and medium length feeders (typically 80 km to 300 km). A load centre, where density is at its greatest level is generally the focus of the area where the community's business district is situated. Energy requirements dissipate as the distribution of energy moving away from this centre. Further to the challenges that present themselves for the regional situation, is that many industrial spot loads are connected to the network and each has a unique effect on the network's PQ [14].

Rolling out optical fibre as a communication channel to link all nodes in this scenario is not a cost-effective approach to achieve DSA [29]. Optical fibre could be used to connect the nodes, specifically within the load centre where load density is at the highest level and wireless solutions, PLC signals or Broadband over Power Lines (BPL) provide possible solutions for the other regional areas.

The wireless installation is for locations that distances between nodes would be the greatest and the expense of optical fibre cannot be justified. Such an instance would be the communication link from the regional centre to the central command centre which could be hundreds of kilometres apart with no significant load centre(s).

2.3.3. Rural and remote

The feeders with the length over 300 km are extremely unreliable and have low PQ, weak voltage profile and large system losses. The load density of such regions is low in comparison to CBD scenarios. Rural systems contain sectionalisers and reclosers as means to limit the impact of a faulted section of feeder on the rest of the rural network [14]. The long radial nature of a rural and remote feeder does not lend itself well to the installation of hardwired DSA communication solutions. The most cost-effective solution of a communication channel for DSA in rural environments is a wireless system. The coverage that a wireless system can achieve far exceeds any wired solution currently available and can effectively achieve the desired outcomes of DSA.

2.3.4. Entire system

The integration of these three scenarios is essential for the entire DSA concept to be functional. Information and control signals from the remote and regional electrical systems need to propagate from the point of origination to a central command for decision support. The wireless system sends the information from the remote transmitters to a receiver station, where there can be a wired link to the rest of the regional and CBD networks. The Australian terrain would have to implement such a system to achieve DSA, otherwise, the full potential of such a system would not be realised. Trails of DSA solutions have been implemented by ACTEW similar to those referenced in the CBD, Regional and Rural subsections explained above [14].

3. Protection scheme automation

At the heart of any distribution system, the protection scheme is located to prevent any damage to the connected equipment during adverse operating conditions. From the outset of developing the first energy distribution system, protection was seen as a major issue that is needed to be addressed for the system to be viable in delivering the power required [30].

There is no greater need in today's distribution system than to protect against PQ disturbances. This is mainly due to the ever increasing sensitivity and highly expensive equipment connected to the supply and the financial repercussions of damaging of such equipment [15]. Most protection schemes in use today are essentially automated from the time the fault and the isolation of the faulted section occur. The inefficient task of manually locating and closing in, on a fault is not automated and it is here that DSA can have the greatest effect [12].

3.1. Role of protection in DSA

After the initial lock out of the faulted section of network occurs, the arduous task of locating the fault and restoring supply begins. Currently, this is done manually with only vague information as to the location of a fault and whether the fault condition continues to inhibit supply. There is a great potential that, during fault conditions on the networks, the fault could be isolated and unaffected customers can be returned to supply [31]. Simultaneously, DSA provides a mean to dispatch work crews to fault site location in order to assess the situation and restore the network to normal conditions. Through logic expression specific to the network and intelligent devices, this objective is achievable [12].

3.1.1. Protection using logic based decision

Any specific section of network can be reconfigured in the event of a fault on this section of network to return unaffected customers to supply. In this regard, various local and remote network status indicators need to be available to all network protection devices in order to completely realise the potential of protection systems in DSA [31]. Using these network status indicators along with logic-based protection decisions can greatly increase the reliability of the distribution system and reduce the operation costs [12]. Furthermore, customer's satisfaction is enhanced as a process of the increased reliability.

Logic can be used on cross feeder ties which are normally open points within the distribution network and on sectionalising reclosers that isolate the faulted sections of the network [12]. For example, in Fig. 12, a fault at F1 or F2 is considered. A fault at F1 in a logic-based protection scheme forming part of DSA would trip out recloser 1A to isolate the fault as a part of the system protection. This process of isolating the faulted section of the feeder is a part of the normal operation of a current distribution system. The similarities with current distribution systems end from this point forward with automation replacing the manual restoration of supply to customers.

Automation of restoring supply in the case of F1 requires 1B to open and recloser 3 to close when 1A trips on the fault. This can be implemented, if all reclosers on the network are aware of local as well as remote conditions of the network. The recloser 1B would know in this case that an alternative source is available and it is possible to 'back feed' to continue supply to customers between reclosers 1B and 3. Simultaneously, recloser 3 would notice volts on one side of this cross feeder tie and no volts on the other side of this isolation point and possesses the information that 1A tripped, therefore would conclude to close from its normally open position.

A fault at position F2 on the network would result in 1B locking out and recloser 3 remaining open as it has received information that 1B has tripped and therefore, it is not beneficial to close in

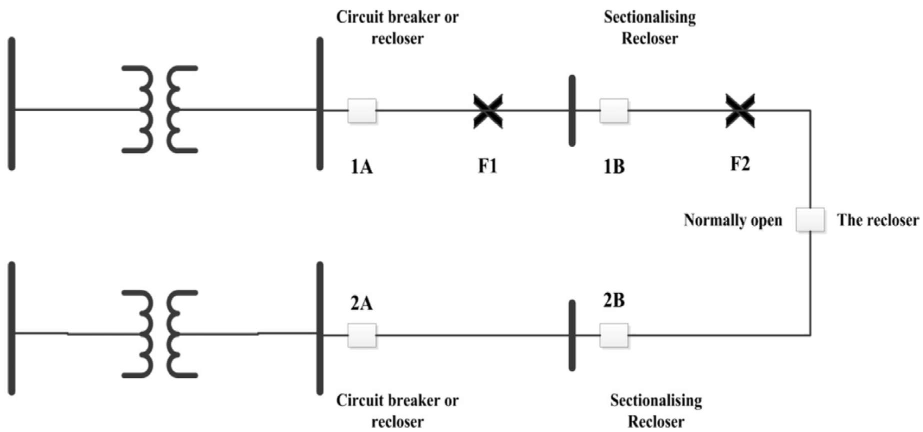

Fig. 12. Recloser loop [12].

this instance, keeping the fault isolated. This is a basic example of how logic could work within a 3 recloser loop DSA protection scheme [12].

3.1.2. Logic and IEDs

The importance of both remote and local network status indicators becomes clear when logic-based protection decisions are programmed into network protection devices. All available data relating to the status of the network must be acquired for the intelligent devices to make fast and accurate decisions as to what actions are the best for any specific fault [27]. The integration of Motes and IEDs as parts of this logic-based protection scheme is essential to the system's operation and multiple benefits can be achieved through this interaction.

The basic example detailed in the previous item would be implemented through the programming of the programmable logic device and the installation of tools for communication between devices. The IED has the logic programmed into the device while the mote provides the means for communication between network devices. The network status indicators are sent over the communications channel via the mote which then feed these signals to the IED. The IED uses these signals and the logic programmed into devices to make protection decisions when the need arises.

What makes the mote and IED pair desirable is the process of remote reprogramming of logic due to subsequent modification of the network. Any permanent or temporary change to the network would require that the IEDs being reprogrammed to perform different tasks under different fault conditions and therefore, the logic on these devices would have to be changed. The mote provides the chance to reprogram the device remotely from a central position where numerous changes can be made efficiently [23].

This is particularly used when a section of network needs to be isolated in order to complete maintenance or to augment the network. To work safely on this section, there may have to be a number of devices reprogrammed to not close in, on the work site when there is a fault on the another section of the related network. Once the work is completed, the IEDs need to be returned to the original programmed logic or reprogrammed to a suitable logic after network modification.

4. Network reconfiguration

The prospect of network reconfiguration provided by DSA enables energy distribution companies to achieve higher efficiencies in the case of power delivery to their customers. Feeder load balancing allows energy utilities to gain added operational control of their electrical assets and in the process, provide more quality service in energy distribution [32]. Feeder load balancing and network reconfiguration benefits are discussed in the next sections.

4.1. Feeder load balancing

Balanced three-phase energy distribution systems provide the greatest efficiency in power delivery. Today's energy distribution system is rarely balanced and feeder balance is generally unachievable for all given times of operation. This is due to loads on a feeder switching in and out of operation at various demand periods producing imbalance with other feeder loads. In conjunction with DSA and the implementation of feeder load balance systems, the energy distribution network can be continually balanced for both real and reactive power [32].

4.1.1. Balancing real power load

The ultimate goal of feeder load balancing is to avoid overloading sections of network during peak demand and gaining higher utilisation of electrical assets as a process. The normal operation of the distribution network is radial in nature with sectionalising and cross tie switches used for protection and network reconfiguration. Feeder load balance is achieved through shifting loads from one feeder to the next made possible by numerous switching options available as a consequence of sectionalising and cross tie switches [33].

Cross feeder ties in traditional distribution networks are switches that are normally open points between sections of feeder to allow transferring loads from one feeder to another and vice versa. Sectionalising switches are alternatively closed points along a feeder and used for isolation and protection. In the automated network configuration, a cross tie switch can be closed and a sectionalising switch can be opened to transfer the load of one feeder to an adjoining feeder to achieve feeder load balance. The cross feeder tie is now acting as a sectionalising switch and the sectionalising switch is acting as a cross feeder tie implying the dual nature of such switches in the automated system [33].

The network reconfiguration for feeder load balancing is desirable during peak demand periods. Reconfiguration has added benefits in providing optimal operational conditions, if real-time analysis is continually sought. This real-time application induces complex mathematical problems for finding the optimal or near optimal configuration [34]. Many mathematical algorithms have been proposed as solutions to the complexity of network reconfiguration which will be discussed in Section 4.2.

4.1.2. Balancing MVAr load

In monitoring Real power indicators, it is equally significant to monitor the reactive power indicators within a network. Some commercial and industrial loads are inherently reactive in nature reducing the power factor of the network and introducing system losses and inefficiencies. By balancing the MVAr loads within the distribution network, it may be possible to reduce system losses and enable more effective power factor correction in response to reactive loads [16].

Balancing reactive loads would be done in a similar manner to that described for real power applications and would be definitely carried out, simultaneously. Challenges on balancing this reactive load become obvious when investigating the reactive power density of industrial parks wherein such measures are generally higher than the density of residential loads. This must be overcome as it has been recognised for some time now that returning the power factor of the energy distribution network to as close as possible to unity is a highly desirable outcome [16].

4.2. Optimal network algorithms

The optimisation of the network through network reconfiguration has been proven to be vastly more complex than originally thought. Yuan-Kang et al. [35] presents a methodology for distribution system reconfiguration using an Ant Colony Algorithm (ACA) in order to minimize power loss and increment load balance factor of radial distribution systems that contains DGs. A multi-objective framework has been presented by Amanulla et al. [36], for distribution system reconfiguration in order to simultaneously minimize the system's real power loss and maximize the reliability. Moreover, Kavousi-Fard and Niknam [37] presented a model for reliability enhancement of the distribution system through reconfiguration strategy. This model concurrently takes into account the cost due to active power losses and the costs of customer interruption in a cost function. Rao et al. [38] proposed a method to deal with the problem of distribution system reconfiguration considering DGs. This problem is modeled as an optimisation problem with the objective of real power loss minimization and it is solved using Harmony Search Algorithm (HSA) to concurrently reconfigure and determine the optimal locations for installing DG units.

The re-switching of the network to provide feeder load balance presents many opportunities for efficiency; on the contrary, it has also revealed inadequacies in computational speed of optimisation algorithms [34]. A Current Index Based Load Balance Technique as well as the Branch Exchange Algorithm are used to address the complexity of the optimal network configuration problem as investigated below. This technique calculates a current index for any particular network configuration and compares this to a formulated set of previously calculated current indexes. The lowest current index calculated amongst all feasible switching options is the optimal or near optimal network configuration [39]. The Current index is calculated as:

$$F_B = \left(\frac{\Delta PR}{(PR_{\max} - PR_{sys})} \right)^2 \tag{1}$$

where,

$$\Delta PR = \max \left[|PR_r - PR_{sys}, \ |PR_b - PR_{sys}| \right] \tag{2}$$

F_b is the feeder current index for balance and PR is the loading percentage ratio [39].

The Branch Exchange Algorithm proposed by Kashem et al. [34], initially formulates an optimisation solution using heuristic methods which is generally a locally optimal solution but may not be the global optimal or near optimal solution desired for the system operation. The algorithm then identifies all feasible switching options and calculates load balancing index (LBI) of the system [34]. The equation for the LBI of the system is found below with S_i denoting the complex power flowing through the ith branch, $S_i^{\max}$ is the maximum rating of the ith branch and n_b is the number or branches in the system [34].

$$LB_{sys} = \frac{1}{n_b} \sum_{i=1}^{n_b} \frac{S_i}{S_i^{\max}} \tag{3}$$

The algorithm exhausts all feasible switching options calculating this load Balancing Index Until it reaches a minimum LBI and an optimal or near optimal solution is found. Note that, a feasible switching option is where no connected loads are isolated and no closed loops are created. Moreover, constraints must be also satisfied with the nodal voltage to be within a permitted range, capacity and ratings of electrical assets not to be exceeded and the system losses to be at minimum [34].

In comparison to other algorithms used to address the complexity of network optimisation, branch exchange has many valuable benefits. The major benefits chiefly include the computational speed and the accuracy of the optimal or near optimal solution obtained by this method [34]. In dealing with real-time applications, these two aspects of automation form part of the most critical issues when dealing with optimisation. The solution must be accurate and converge quickly so that optimal or near optimal solution can be implemented and the benefits of such a configuration can be achieved.

Table 1 shows the comparison between the branch exchange method and the Current Index Algorithm.

4.3. Benefits of feeder load balance

By integrating feeder load balance into any DSA system, immense benefits and desirable outcomes are achieved. Feeder load balance enables a distribution company to gain operational efficiencies through loss minimisation and system stability [33]. These benefits are discussed below in relation to DSA and network reconfiguration addressing why these benefits above all others are highly desirable as a consequence of feeder load balance.

4.3.1. Loss minimisation

By reconfiguring the network for feeder load balancing, loss minimisation can be achieved. The minimisation of loss is inextricably related to the balancing of loads across feeders, significantly reducing

Table 1
Comparative study [34].

Branch exchange	Current index
• Constraints such as voltage limit and system loss are considered for finding optimal solution • Easily applied to any large system in practice as it is able to determine optimal solution with minimum computational effort and time, proven for 69-bus test system • Load balancing of every branch in each feeder has been considered	• Constraints are not imposed explicitly, thus the solution may lead to increased system loss and/or violating voltage limit • Search will be exhaustive, particularly for larger system in practice and computational effort and time will be much higher. The considered test system is a small hypothetical system • Load balancing of every feeder only is considered

the real power losses that occur during traditional distribution system operation [33]. The Branch Exchange Algorithm explained in the previous section involves the calculation of a Load Balance Index which effectively calculates power loss over the distribution network for any switching option. By selecting the lowest feasible LBI, the algorithm invariably selects the network configuration that incurs the lowest losses and therefore, is the optimal or near optimal solution [34].

Loss minimisation is desirable to distribution companies for several reasons including high utilisation of electrical assets, lower operational costs and fewer electrical asset tap changes. All these outcomes lead to real savings in operational costs and can even defer various capital investments, such as asset replacement for sometimes indefinite periods of time [16]. Loss minimisation appears to be the major contributing factor in the desired implementation of network reconfiguration and DSA [32].

4.3.2. *System stability*

Voltage stability is another important outcome of network reconfiguration and feeder load balance. The reconfiguration of the network to alleviate overloading of feeders allows any voltage instability associated with such conditions to be avoided. By mitigating the risk of voltage and system instability through network reconfiguration, it can be seen that, instances of voltage drop and voltage loss due to overloading decrease, dramatically. It has also been proven in research papers that, by finding the network configuration that incurs minimal power losses as a consequence also exploits system voltage stability [32]. Distribution companies gain system stability from network reconfiguration and therefore, they are able to deliver more reliable energy. Due to both system stability and loss minimisation, any connected customer that receives its energy from a utility using network configuration will consistently receive higher PQ and a more reliable energy service delivery compared to customers connected to traditional utility networks.

5. Renewable and distributed generation control through DSA

Distributed generation (DG) is the generation connected to lower voltage levels found in the distribution system, typically at 400 V and 20 kV voltage levels. It is generally of low capacity and small output, but can provide support to the distribution system during periods of system stress [40]. Such examples of generation connected at the distribution level are solar, wind, wave and geothermal generation as well as small gas turbines typically situated at mining and waste disposal sites. A comprehensive review of distributed multi-generation (DMG) like combined heat and power (CHP) generation has been conducted by Chicco and Mancarella [41] that the DMG structures have been summarised. The power sector has been interested in DG, particularly to decrease power loss, increased reliability and also to reduce emission [42,43]. For this purpose, Borges [44], has presented a comprehensive review on reliability models and methods employed to estimate Renewable Energy Sources (RESs) affecting the electric generation availability. Integrating DGs into distribution networks may bring several challenges in the case of unintentional islanding, such as PQ, safety, voltage and frequency stability and interference [45]. In this regard, Heidari et al. [46] has proposed an intelligent-based islanding detection technique.

Another aspect of RESs would be their intermittent nature that some of them are involved with, like wind power generation. Thus, it is necessary to exist an energy storage system to mitigate this shortfall [47].

5.1. *DG benefits*

DG provides many benefits to the distribution industry in supplying energy to its connected customers. DG can meet additional peak demand that utilities may have trouble in supplying through the traditional Base Load generation. Base Load generation techniques generally provide large centralised capacity, but may not be able to provide the additional capacity needed during peak demand periods, such as during extreme heat or extended cold weather. DG technologies such as solar and wind power are suitable solutions to supply the extra demand required by the distribution system during the extreme weather condition periods whilst also providing renewable sources of energy [40]. DG when used to alleviate peak demand concerns forms part of a concept known as DSM.

5.2. *DG problems*

DG whilst providing many benefits to the distribution system can also induce many problems associated with the connection of the additional supply to the grid. A vast majority of issues are introduced when connecting DG to the distribution grid is concerned with the matching of all waveform parameters between the grid and the DG supply. The frequency of DG source, synchronisation of DG waveform with the grid and matching of voltage profile of DG source with the grid are just some of the problems associated with the connection of DG [48].

Further to the synchronisation problems encountered in the connection of DG to the distribution system, is the power electronic equipment to facilitate this connection. Many DG systems generate energy sporadically or produced in DC form. The power electronics transforms the generated waveform from an inconsistent mess to a more pure waveform making it able to be connected to the distribution system. The problem with these high-powered electronic systems is that they themselves introduce unwanted disturbances into distribution grid through their operation [40]. The control of these undesirable features of DG is essential to the success of the DG program with the integration of DG control into DSA.

5.3. *DSA control of DG as a DSM program*

The delivery of DSM schemes relies mainly on the accurate real-time data and the ability to quickly enact DSM procedures when appropriate to gain the most advantage to the distribution system. The real-time data is provided by the IEDs while the data is collected and transmitted by the proposed communication system. The process of notifying the DG sources to be switched in or out of service occurs once the decision is reached by the automated system to engage DSM. Two possible methods of achieving this outcome are through ripple control methods and through broadcasting [49].

5.3.1. *Ripple control*

Ripple control technology is nothing new to the distribution industry. The Off-Peak hot water system is a ripple control system that has been used by utilities for decades to control electrical hot water systems in the residential household. This is done by injecting a high frequency signal usually at the zone substation level into the voltage waveform which is detected by a relay. The relay switches the hot water system on or off, effectively managing the heating load during the maximum demand periods [50].

The system described above is instigated on a time basis when utilities propose the demand for power will be at a minimum and therefore, the switching of additional load into the system would put little stress on distribution system. On the contrary, ripple control system that would be used by DSA to switch in and out DG sources during peak demand would be based on demand readings taken by IEDs. A ripple control system initialised solely on time is not ideal due to the timing of the maximum demand being inconsistent day to day as well as for each section of the network [50]. In the proposed DSM control system for DG switching, the ripple control would be initialised through the collection and analysis of real-time data. If the data suggests that the network is overloaded and the distribution system is under stress, certain measures are needed to alleviate system stress. DSA would calculate the optimal solution for DG source input and initialise the ripple control to effect the desired DG source switching.

There are several problems associated with the use of ripple control to effect the switching of DG sources in and out of connection with the grid. The chief concern is the inevitable delay in signal propagation. When a quick and succinct response is required to protect distribution network equipment and to ensure continuity of supply to customers, it is imperative that no delays are unnecessarily introduced to the response time. Whilst this is a major problem of ripple control, the system still provides benefits including security of control signals and low set up cost. Control signal security is seen as an important advantage of ripple control over other control signal techniques [50].

5.3.2. Broadcast control of DG sources for DSM

To improve the response time of a control system that alleviates the overloaded conditions of the network, the use of a broadcast signal was suggested. Broadcast control can be used in a similar method to PLC except that the signal is propagated through a broadcast technology such as a wireless network, Next Generation network or radio signal. This method is faster at signalling DG control but can have security issues with signals.

6. Conclusion

Recent advances in technology considerably help the power distribution systems to move towards intelligent networks. In this regard, this paper investigated the DSA technologies like intelligent electronic devices (IEDs) and Motes and discussed the advantages and disadvantages of current systems. Moreover, DSA has been reviewed in the context of Australia. Network reconfiguration is another key point provided by DSA which is discussed in this paper. Furthermore, DG in the context of distribution system automation associated with DSM is an important issue scrutinised in this paper, while the role of protection system as the heart of distribution systems was stated and investigated from the system automation's point of view. However, it seems necessary to more investigate and assess the different aspects of distribution system automation in detail.

References

[1] Gupta R, Varma R. Power distribution automation: present status. Acad Open Internet J. 2005;15.

[2] Hauser CH, Bakken DE, Bose A. A failure to communicate: next generation communication requirements, technologies, and architecture for the electric power grid. IEEE Power Energ Mag 2005;3:47–55.

[3] Y Pradeep, S Khaparde, R Kumar. Intelligent grid initiatives in India. In: International conference on intelligent systems applications to power systems, 2007 (ISAP 2007); 2007. p. 1–6.

[4] ZA Vale, H Morais, M Silva, C Ramos. Towards a future SCADA. In: IEEE power & energy society general meeting, 2009 (PES '09); 2009. p. 1–7.

[5] SCADA systems for electric power industry e five year market analysis and technology forecast through 2011, ARC Advisory Group; 2007.

[6] Ilic MD. Dynamic monitoring and decision systems for enabling sustainable energy services. Proc IEEE 2011;99:58–79.

[7] Metke AR, Ekl RL. Security technology for smart grid networks. IEEE Trans Smart Grid 2010;1:99–107.

[8] Kang DJ, Lee JJ, Kim BH, Hur D. Proposal strategies of key management for data encryption in SCADA network of electric power systems,. Int J Electr Power Energy Syst 2011;33:1521–6 11//.

[9] S Lee, D Choi, C Park, S Kim. An efficient key management scheme for secure SCADA communication. In: Proceedings of world academy of science, engineering and technology; 2008.

[10] Rezai A, Keshavarzi P, Moravej Z. Secure SCADA communication by using a modified key management scheme. ISA Trans 2013;52:517–24 7//.

[11] X Liangliang, IL Yen, F Bastani. Scalable authentication and key management in SCADA. In: IEEE 16th international conference on parallel and distributed systems (ICPADS), 2010; 2010. p. 172–179.

[12] LA Kojovic, T Day. Advanced distribution system automation. In: IEEE PES transmission and distribution conference and exposition, 2003; 2003. p. 348–353.

[13] A Muji, N Suljanovi, M Zajc, J Tasi. High-voltage PLC roles in packet-switching networks of power utilities. In: IEEE international symposium on power line communications and its applications, 2007 (ISPLC'07); 2007. p. 204–209.

[14] J Cornell. Philosophy for operation of distribution system automation schemes: ACTEW's approach. In: Proceedings of international conference on energy management and power delivery, 1995 (EMPD'95); 1995. p. 37–42.

[15] DM Staszesky. Use of virtual agents to effect intelligent distribution automation. In: IEEE power engineering society general meeting, 2006; 2006. p. 6.

[16] M Dixon. Autoadaptive volt/VAr management system. In: Rural Electric Power Conference, 2001; 2001. p. D4/1–D4/8.

[17] P Foord, J Tsoucalas. Remote meter reading, load control and distribution system automation utilising SWD technology. In: Sixth international conference on metering apparatus and tariffs for electricity supply, 1990; 1990. p. 163–167.

[18] Bouford JD, Warren CA. Many states of distribution,. IEEE Power Energ Mag 2007;5:24–32.

[19] Hor C-L, Crossley PA. Unsupervised event extraction within substations using rough classification,. IEEE Trans Power Delivery 2006;21:1809–16.

[20] Y-r Choi, MG Gouda, MC Kim, A Arora. The mote connectivity protocol. In: Proceedings the 12th international conference on computer communications and networks, 2003 (ICCCN 2003); 2003. p. 533–538.

[21] Hor C, Crossley P. Substation event analysis using information from intelligent electronic devices,. Int J Electr Power Energy Syst 2006;28:374–86.

[22] Warneke B, Last M, Liebowitz B, Pister KSJ. Smart dust: communicating with a cubic-millimeter computer,. Computer 2001;34:44–51.

[23] RM Kling. Intel motes: advanced sensor network platforms and applications. In: IEEE MTT-S international microwave symposium digest, 2005; 2005. p. 4.

[24] Gorder P Frost. Sizing up smart dust,. Comput Sci Eng 2003;5:6–9.

[25] P Triantafillou, N Ntarmos, S Nikoletseas, P Spirakis. NanoPeer networks and P2P worlds. In: Proceedings of third international conference on peer-to-peer computing, 2003 (P2P 2003); 2003. p. 40–46.

[26] H Zhao, K Chon. A portable, battery-powered wireless monitoring system with localized data analysis. In: IEEE 33rd annual northeast bioengineering conference, 2007 (NEBC'07); 2007. p. 273–274.

[27] Hor C-L, Crossley PA. Extracting knowledge from substations for decision support,. IEEE Trans Power Delivery 2005;20:595–602.

[28] Chan H, Perrig A. Security and privacy in sensor networks. Computer 2003;36:103–5.

[29] Kirkham H, Johnston AR, Allen GD. Design considerations for a fiber optic communications network for power systems. IEEE Trans Power Delivery 1994;9:510–8.

[30] Adamiak M, Redfern M. Communications systems for protective relaying. IEEE Comput Appl Power 1998;11 14–18, 20–2.

[31] L.A. Kojovic. Advanced protection solutions for improved power system dynamics performance. In: IEEE PES power systems conference and exposition, 2004; 2004. 1:581–586.

[32] Kashem M, Ganapathy V, Jasmon G. Network reconfiguration for enhancement of voltage stability in distribution networks. IEE Proc-Gener, Transm Distrib 2000;147:171–5.

[33] M Kashem, M Moghavvemi. Maximizing radial voltage stability and load balancing via loss minimization in distribution networks. In: Proceedings of international conference on energy management and power delivery, 1998 (EMPD'98); 1998. p. 91–96.

[34] Kashem M, Ganapathy V, Jasmon G. Network reconfiguration for load balancing in distribution networks. IEE Proc-Gener, Transm Distrib 1999;146:563–7.

[35] Yuan-Kang W, Ching-Yin L, Le-Chang L, Shao-Hong T. Study of reconfiguration for the distribution system with distributed generators. IEEE Trans Power Delivery 2010;25:1678–85.

[36] Amanulla B, Chakrabarti S, Singh SN. Reconfiguration of power distribution systems considering reliability and power loss. IEEE Trans Power Delivery 2012;27:918–26.

[37] Kavousi-Fard A, Niknam T. Optimal distribution feeder reconfiguration for reliability improvement considering uncertainty. IEEE Trans Power Delivery 2014;29:1344–53.

[38] Rao RS, Ravindra K, Satish K, Narasimham SVL. Power loss minimization in distribution system using network reconfiguration in the presence of distributed generation. IEEE Trans Power Syst 2013;28:317–25.

[39] W-M Lin, H-C Chin. A current index based load balance technique for distribution systems. In: Proceedings of international conference on power system technology, 1998 (POWERCON'98); 1998. p. 223–227.

[40] J Dolezal, P Santarius, J Tlusty, V Valouch, F Vybiralik. The effect of dispersed generation on power quality in distribution system. In: CIGRE/IEEE PES international symposium quality and security of electric power delivery systems, 2003 (CIGRE/PES 2003); 2003. p. 204–207.

[41] Chicco G, Mancarella P. Distributed multi-generation: a comprehensive view. Renewable Sustainable Energy Rev 2009;13:535–51.

[42] Labis PE, Visande RG, Pallugna RC, Caliao ND. The contribution of renewable distributed generation in mitigating carbon dioxide emissions. Renewable Sustainable Energy Rev 2011;15:4891–6.

[43] Tan W-S, Hassan MY, Majid MS, Rahman H Abdul. Optimal distributed renewable generation planning: a review of different approaches. Renewable Sustainable Energy Rev 2013;18:626–45.
[44] Borges CLT. An overview of reliability models and methods for distribution systems with renewable energy distributed generation. Renewable Sustainable Energy Rev 2012;16:4008–15.
[45] Khamis A, Shareef H, Bizkevelci E, Khatib T. A review of islanding detection techniques for renewable distributed generation systems. Renewable Sustainable Energy Rev 2013;28:483–93.
[46] Heidari M, Seifossadat G, Razaz M. Application of decision tree and discrete wavelet transform for an optimized intelligent-based islanding detection method in distributed systems with distributed generations. Renewable Sustainable Energy Rev 2013;27:525–32.
[47] Toledo OM, Oliveira Filho D, Diniz ASAC. Distributed photovoltaic generation and energy storage systems: a review. Renewable Sustainable Energy Rev 2010;14:506–11.
[48] L Kojovic. Impact DG on voltage regulation. In: IEEE power engineering society summer meeting, 2002; 2002. p. 97–102.
[49] De Almeida AT, Vine EL. Advanced monitoring technologies for the evaluation of demand-side management programs. Energy 1994;19:661–78.
[50] D Raisz, AM Dan. Ripple control as a possible tool for daily load balancing in an open electricity market environment. In: IEEE Russia Power Tech, 2005; 2005. p. 1–6.