Master of Engineering

Investigation of the applicability of Power Line Communications for Smart SWER

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The work contained in this thesis has not been previously submitted either in whole or in part for a degree at CQUniversity or any other tertiary institution. To the best of my knowledge and belief, the material presented in this thesis is original except where due reference is made in text.

Signed:

Date:

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I would like to thank CQUniversity and the following people for allowing me to learn and grow as an engineer.

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Abstract

Power quality issues such as voltage sags, swells and flicker are well documented on Single Wire Earth Return (SWER) systems with the effects until recently disregarded. The increase in consumer electronics and electronic control systems in loads has meant these issues can no longer be ignored. To provide greater stability to the distribution systems in an attempt to combat these issues, autonomous strategies such as line augmentation, switched shunt reactors, Line Voltage Regulators and Thyristor Controlled Reactors have been trialed, each with an associated cost and degree of success.

One significant issue that has been raised as more dynamic devices become part of a once static system is that of coordination and regulation. In building a more efficient, smarter network, a degree of device autonomy will be eroded to facilitate a more holistically managed system. This can only be accomplished through communication between smart devices themselves and reporting to utilities, which in turn will require a communications medium.

This thesis looks at the possibility of using the power distribution system as the communication medium. It reviews the physical constraints of SWER systems in terms of their intrinsic parameters and derives the system capability for information propagation within the CENELEC guidelines for power line communications. It examines the issues of signal attenuation due to SWER cable parameters over the CENELEC bandwidth and models the channel capacity as a function of both the signal to noise ratio and channel parameters.

The findings of this research demonstrate the potential for Power Line Communications over SWER networks, and associated limitations. It suggests the possibility of limited control and reporting signals at channel capacities of around 14kbps for distances of 100 kilometers with a signal to noise ratio of -30dB. These capabilities would certainly provide a useful communications mechanism for a smart network.

1 Overview

1.1 Introduction

> *In the future, the importance of electricity can only increase. In fact, electricity will be one of the keys for solving two of the 21st century's great energy challenges* [1].

The two challenges referred to in the quote from Lighter and Scheer are that of the US oil import dependency and green house gas emissions. These challenges are not restricted to the US however, but are a global concern. In Australia, energy production and use accounts for 40% of our green house gas emissions [2].

Electrification was voted "*Most significant engineering achievement of the 20th Century*" by the National Academy of Engineering in the US, while the Internet rated thirteenth [3]. To a great extent, the transmission system (known as *the Grid*), that supplies the cities, towns and industries making up the fabric of our society, goes largely unnoticed in day to day life. With the increase in power demand associated with societies increased uptake of technology however, the capacity of the grid to deliver power is being stretched [3]. While augmentation investment is required to help meet the demand, efficiencies associated with power delivery and usage need to be considered also. As an example, a 5% increase in grid efficency in the US would equate to a green house gas emissions saving equivilent to the removal of 53 million cars from the road [3].

To increase grid and usage efficiency, a better knowledge of system and user characteristics are required. Monitoring grid infrastructure and changing demand patterns will provide the key to unlocking the full potential of our current electricity distribution systems and providing effective augmentation in the future.

1.2 Problem definition

To provide cost effective electricity to rural and remote areas of Australia, traditional transmission methods have been forgone. These methods, effective in more densely populated and industrial areas, require disproportionate infrastructure and maintenance to be viable in sparsely populated regions. Instead, a distribution system using a single wire for the supply and the earth as the return loop has been developed over the last sixty years [4].

The primary factor in the take up of Single Wire Earth Return (SWER) technology around the world is its low initial infrastructure cost. The simplicity of SWER systems, demonstrated in Figure 1.1 showing a 25kVA consumer load point at Stanage Bay, Queensland, is the key to their cost efficiency and reliability. The capital cost saving reported in [4] for SWER over 2 wire single phase distribution solutions is 50%, with 70% savings made over three wire, three phase solutions. The technology has so far proven to be both reliable and cost effective in terms of infrastructure maintenance with estimated maintenance cost savings of 50% over two and three wire solutions [5].

As a result, Australia now has one hundred and ninety one thousand kilometres (191 000 km) of SWER line servicing rural areas with an estimated infrastructure investment of several billions of dollars [7]. As demand for power increases in rural areas serviced by SWER networks, many are reaching their distribution capacity and are suffering from associated power quality issues[6]. Voltage fluctuations, load induced transients and system capacity have however, proven to be manageable via established and emerging technologies. Energy augmentation for SWER is currently being investigated [8] and may prove critical in offsetting future infrastructure augmentation. To realise the capacity of these individual systems in the creation of a stable, monitored network, communications between devices and the utilities managing the network are imperative.

1.3 Project Objectives

By using the SWER conductor to transmit information between smart devices around a network as well as deliver power to customers, feedback from network

Figure 1.1: Typical SWER customer connection (Stanage Bay, Qld) [6].

infrastructure can be gathered. Based on a complete network picture, commands can be issued to smart devices to adjust their parameters, optimising energy delivery efficiency, power quality and network capacity. Providing data communications between points on a power network however, while conceptually easy, poses many interesting problems.

This Thesis will examine the transmission characteristics of SWER lines, including noise and channel capacity analysis, along with multipath effects and establish the parameters for further channel modeling. This work is essential for the further study of communication techniques and their applicability to solving SWER power line communication(PLC) issues, assisting in the eventual development of smart SWER.

1.4 Research methodologies and techniques

This report will provide a review of current SWER network issues, including mitigation techniques, and an overview of Smart grid technologies and topologies that may provide insight into the realisation of Smart SWER. The design of any communication system begins with an investigation into the medium through which the signal (sound waves, electrical pulses, electromagnetic waves etc) travels. In this research the investigation will focus on, and will include;

- A comparison of the physical characteristics of common SWER transmission lines and three phase systems,
- An investigation of channel capacity based on derived SWER parameters incorporating the effects of attenuation,
- An investigation into channel noise sources relative to SWER environments.

The Thesis aims to provide the fundamental building blocks for future SWER PLC investigations that can be applied to the many topological SWER network variations that exist.

1.5 Conclusion

Currently, no channel model exists specific to the transmission of data over SWER systems. This Thesis aims to provide this model for future research purposes. Each of the key investigation areas represents a step towards implementing PLC over SWER networks, culminating in the capacity to design and build a smart SWER system. The gains smart SWER may provide to the utility include:

- improved management of the networks capacity,
- improved management of the networks voltage,
- assist in facilitating the implementation and use of distributed generation as an energy augmentation source,
- improved fault monitoring of the network,
- improved customer service through the realisation of smart meters.

With the implementation of Smart SWER, network planning and administration will enter a new level of cost and energy efficiency.

2 Single Wire Earth Return distribution

2.1 Introduction

Australian SWER systems have historically supported several dozen consumers with a total load demand of around 100kW per system [9]. Management of SWER infrastructure is generally provided via routine inspection, planned maintenance and customer reporting of issues. This has proven sufficient due to the simplicity and reliability of the system, with SWER contributing only 24% of lost customer minutes compared to twice that for parent feeders [7].

Changing consumer requirements however, are now highlighting distribution issues previously unseen or now considered unacceptable [10]. Electronics embedded in domestic appliances and the growing use of computers and other electronic technologies in households is raising the profile of power quality. Costs associated with repairing or replacing items damaged by power fluctuations has heightened consumer awareness of the necessity for properly regulated supplies. This, coupled with an expanding consumer base in rural and remote areas, is straining the limits of current SWER infrastructure [11]. Figure 2.1 shows a typical SWER network circuit with 2 customers.

Critical areas of concern for consumers and electricity suppliers on SWER networks are power availability and voltage fluctuations outside of rated guidelines [12][9]. Additionally, utilities are having to manage the unbalancing effect of increased SWER loads on three phase transmission systems [7] with little or no operational visibility.

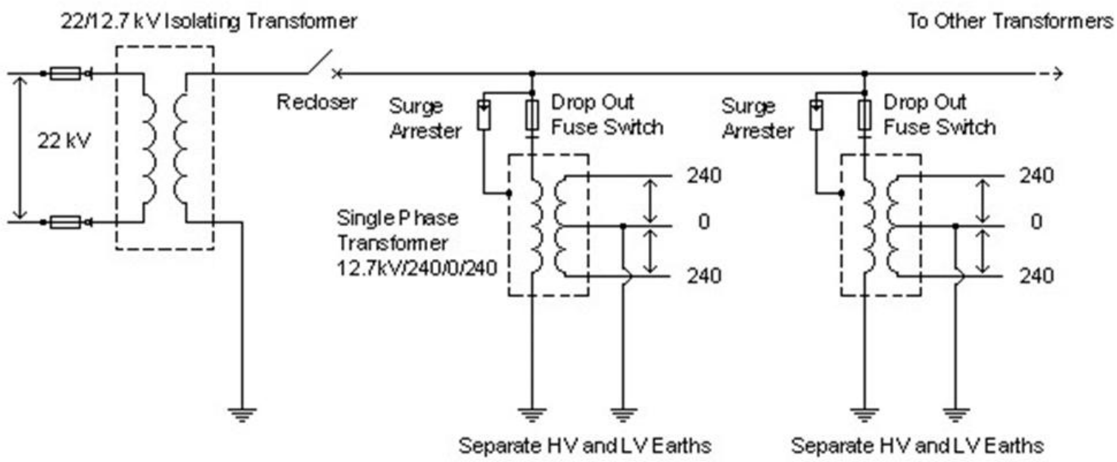

Figure 2.1: Typical 12.7kV SWER network circuit

2.2 SWER system profiles

SWER networks vary in size, load density and supply voltage. Typically, a network is fed via an isolation transformer from two phases of a 22kV (12.7kV SWER) or 33kV (19.1kV SWER) three phase transmission system geographically situated close to end consumers [11]. A backbone conductor is run through the general demand area with tee off's used to service individual or small clusters of consumers [12]. The cable characteristics of a backbone and tee off conductor are given in Table 2.1 for the Jericho North SWER network in central Queensland, Australia [9].

Table 2.1: Typical SWER conductor properties at 50 Hz [9]

	Conductor	Parameters
Backbone	$3/4/2.5ACSR/GZ$	$R0 : 2.02\Omega/km; X0 : 0.802\Omega/km; B1 : 2.086\mu mho/km$
Tee off	$3/2.75SC/GZ$	$R0 : 12.55\Omega/km; X0 : 0.819\Omega/km; B1 : 2.029\mu mho/km$

An effect of line charging currents in longer distribution systems is an increase in line voltage with respect to earth. Known as the "Ferranti effect"[9], it results in higher receiving end voltages than those at the transmitting end under light load conditions. As SWER systems use the earth as the return path and reference, the implications for power quality issues due to the Ferranti effect are much higher. This is limited in three phase distribution systems as the effect is practically identical per phase, with phase to phase voltages remaining unchanged.

The over voltage associated with the Ferranti effect is also dependant on transmission line characteristics. Using the hyperbolic forms for long transmission lines where V_S, I_S, V_R and I_R are the voltages and currents at the source and recieving end respectivly[13].

1. $V_S = V_R cosh\gamma l + I_R Z_C sinh\gamma l$
2. $I_S = I_R cosh\gamma l + \frac{V_R}{Z_C} sinh\gamma l$
3. $V_R = V_S cosh\gamma l - I_S Z_C sinh\gamma l$
4. $I_R = I_S cosh\gamma l + \frac{V_R}{Z_C} sinh\gamma l$

Modelling 350km of 3/4/2.5 ACSR/GZ backbone cable with no load produces a voltage increase of 8.4% or 1.6kV at the end of the line from a 19.05kV isolation transformer. Changing the model parameters to a 3/2.75 SC/GZ Tee Off conductor produces a voltage drop of 6.7 kV or 36%.

SWER distribution conductor types are typically chosen for physical as well as electrical characteristics. They are predominantly small diameter, high strength conductors to enable greater distances between distribution poles [11]. Longer runs consisting of backbone and steel tee off conductors can have a total impedance of 1000 Ohms [7].

Figure 2.2 illustrates the effect of conductor resistance on line voltage over a single 400km conductor with a resistance varying between 12 and 1 ohms per kilometer. The Ferranti effect is clearly visible at lower resistances per kilometre with end voltages rising to around 2.2kV.

Regulation of voltage issues have been further complicated by increased demands on SWER networks. The fundamental capacity of a network is dictated by the isolation transformer rating and current carrying capacity of the distribution conductors. In smaller, lightly loaded networks, capacity exists within the system to allow reactive power flow intrinsic in SWER networks. This capacity is being eroded in growing systems by increased consumer real power demand.

A study of the Jericho North SWER network [9] found the network isolation transformer incapable of supporting the system under no load conditions without some form of control on line charging current. Wolfs demonstrated in [9], to maximize the effective capacity of SWER networks, reactive power control is essential. In providing this, voltage fluctuations under light load can be controlled. In concert with this however, voltage fluctuations associated with conductor parameters and heavier load densities need to be addressed [11]. As the loading of the network is a

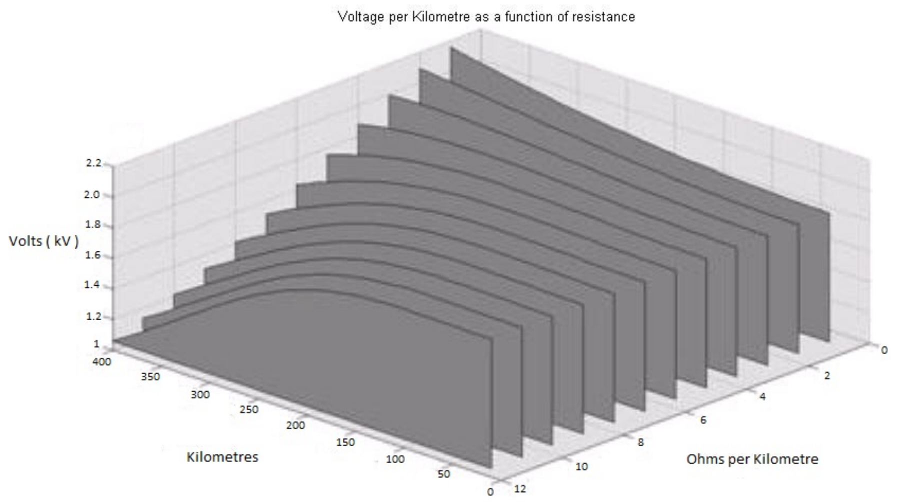

Figure 2.2: The effect of resistance on line voltages.

dynamic process, any solution that can operate successfully at or near full network capacity will also be dynamic. If this can be achieved, the full capacity of current networks can be utilized providing further longevity for current infrastructure.

2.3 Current SWER power quality solutions

Historically, fixed shunt reactors have been used to reduce line charging currents with the following benefits [11]:

- smaller isolation transformers can be used,
- line losses (I^2R losses) are minimised,
- reduction of over voltage issues with longer lines under light load.

Line charging current is the current required to create the electric field between conductor and earth over the length of a SWER network. The effect of this distributed capacitance is the production of reactive power (VARS), unusable by loads to do work as a result of the currents phase relationship with the energising voltage. This effect is reduced through the introduction of inductive loads or shunts, said to consume reactive power [13]. The cycle by cycle energy exchange between the networks capacitive elements and the introduced shunt reactors reduces the reactive current flow required through the isolation transformer under light load conditions.

While fixed shunt reactors have been used to control over voltage problems in light load conditions, they contribute to the emerging under voltage problem resulting from increased loading [9].

2.3.1 Switched Shunt Reactors

Utilities recognise the advantages of removing shunt reactors under heavier load conditions in an effort to regulate voltages to acceptable levels [9]. Since the early 1990's, switched shunt reactors have been investigated as a possible means of controlling over voltage without contributing to under voltage problems [12]. Investigating three methods of automatically switching shunt reactors in [6], Wolfs et al compared the merits of Thyristor Controlled Reactors (TCRs), Contactor Switched Reactors and Consumer Transformer Connected Controlled Reactors. Figure 2.3 illustrates the network model for the Jericho North SWER system used in [9]'s study.

Each technology provided considerable network gains (81%, 84% and 100% respectively) over standard fixed reactors.

Table 2.2 illustrates the effect of each compensation method at specific points in [6]s simulation. As was concluded by [6], switched shunt reactors provide over voltage

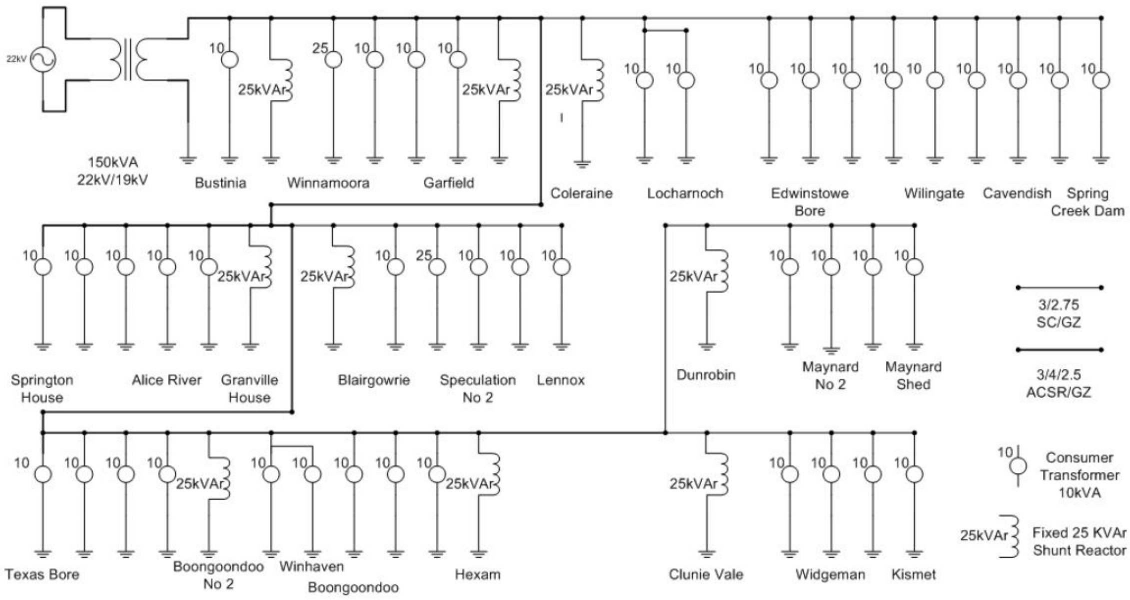

Figure 2.3: Jericho North SWER network [6].

stability and additional capacity to the network under light load. A question to be considered however, is the suitability for each device to manage itself in isolation to other smart devices on the network.

2.3.2 Tap changer transformers

While voltage control can be achieved using static or dynamic reactors, excessive voltage losses due to line impedance cannot be compensated for in this manner. In three phase distribution systems, tap changing on distribution transformers is commonly used to adjust voltages to desired levels for consistent over or under voltage sections [14]. For long SWER networks, off-load tap changing on isolation or distribution transformers cater for voltage drop risks raising the voltage during light load periods above accepted limits [11].

One solution being used to mitigate the light load over voltage issue is to use an on-load tap changer (OLTC). In [15], Myer and van Coller examine the benefits of an on-line tap adjuster in a SWER isolation transformer. While their proposal dealt specifically with voltage drop associated with high impedance lines (40 Ω per km), it is equally viable for the over-voltage adjustment of low impedance lines. By calculating the receiving end voltage drop using pre programmed system parameters, the sending end line voltage can be adjusted accordingly to compensate. While this

Table 2.2: Comparison of solutions for static and dynamic compensation [6].

Location	150kVA Static Shunt	250kVA TCR	250kVA CCR	250kVA CTCCR	
Bustinia	18.59	19	19.07	19.24	
Garfield	18.03	18.33	18.4	18.67	
Coleraine	17.87	18.07	18.13	18.41	
Granville House	17.93	18.22	18.28	18.59	
Blairgowrie	17.72	17.96	18.02	18.42	
Boongoondoo No 2	17.71	18.01	18.07	18.42	
Hexam	17.64	17.95	18.02	18.37	
ClunieVale	17.58	17.88	17.95	18.29	
Dunrobin	17.57	17.86	17.92	18.27	

single controller solution is simple and effective, it is limited in two key areas.

- Myer and van Coller's network model clustered loads at the end of the SWER transmission line. In making this assumption, the effective line impedance between each load point and the isolation transformer is similar. On longer SWER lines, this may not be the case. The result for loads closer to the isolation transformer would be an over voltage relative to their position and the total line loss.
- Any subsequent changes made to the network would require the re-calculation of network parameters and then the re-programming of the proposed OLTC's.

By adding further voltage regulating transformers down stream from the isolation transformer, a more finely granulated control over the network voltage could be gained. Dynamic interaction between OLTC transformers would then need to be considered. If dynamic shunt devices were also present on the network, network stability would become a critical implementation issue.

2.3.3 Line voltage regulators

An emerging technology in the delivery of reliable power quality are Line Voltage Regulators (LVRs). Their principle of operation requires sampling the customer supply, generating a difference voltage between the actual and required output, then injecting this voltage via a series transformer onto the output, as depicted in Figure 2.4.

Trials by Ergon Energy on an LVR solution developed in the USA have been under way since December 2006 [16]. The units are designed to provide a regulated output of 245 ± 1% for input voltages between 205V and 275V with a load capacity of 20kVA.

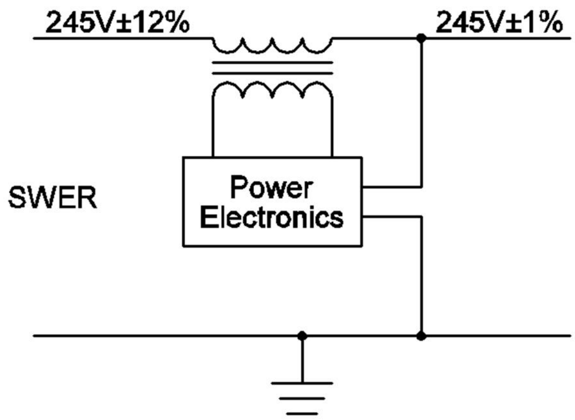

Figure 2.4: LVR principle of operation.

The response time to voltage sags or swells is currently around 200ms (10 cycles), although units with resonse times of 50ms are under design that will provide better flicker mitigation [16].

2.4 Distributed generation (DG) issues on SWER networks

By providing energy augmentation to a distribution network, peak load issues on systems at or near capacity can be alleviated as shown in Figure 2.5 [17]. Energy augmentation can consist of a number of individual technologies (solar, wind, tidal, stored energy etc) or a combination of any. The growth of these technologies and their seemingly inherent applicability to environments currently serviced by SWER networks should see their inclusion in future planning become assured.

McDermott and Dugan raise several technical issues for DG connected to distribution networks. One is the possibility of DG supplying energy to network fault conditions, potentially degrading the network further through a loss of fuse savings in lateral line faults. Other issues cited include misaligned generation and peak loads, DG ownership and system harmonics.

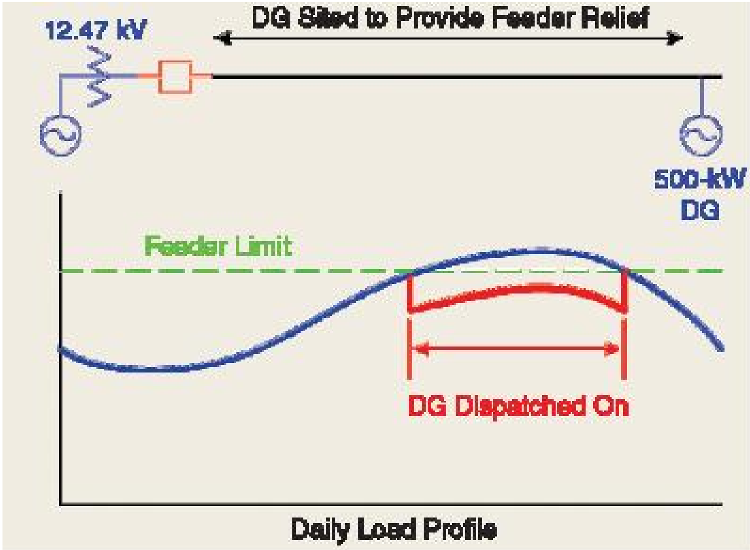

Figure 2.5: DG sited near the end of a feeder lets the utility serve the peak load without exceeding the "feeder limit" [17].

In supporting technologies with energy sources external to SWER distribution systems, consideration must be given to resulting power flows and line voltages [8]. Kashem and Ledwich modelled SWER distribution networks in [8] to determine the dynamic interaction and voltage control effects of applying distributed generation (DG) to the SWER environment. Their studies showed that in low reactance to resistance (X/R) ratio transmission lines as found in SWER networks, voltage profile is most improved by the injection of real power.

Modelling a 120km SWER network at 19.1kV and measuring the voltage per unit (p.u.) over the length of the network, [8] demonstrated the effectiveness of including DG for voltage stability. Comparing the results of their experiments in Figure 2.6 and Figure 2.7, the under voltage limit of 0.94 p.u. (6% under voltage) is reached once before OLTC operation (at 20km), then again after approximately 70km for the non DG simulation (Figure 2.6). For the network including DG however, the lowest voltage recorded is approximately 0.981 p.u. at 85km (Figure 2.7).

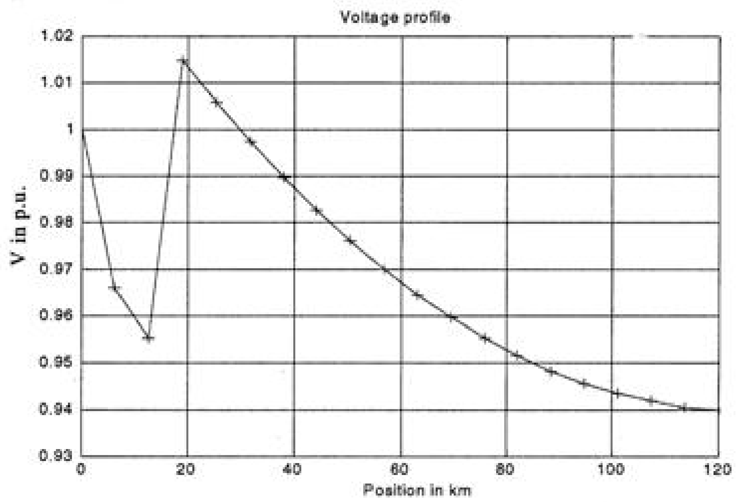

Figure 2.6: Voltage profile with 352kW load without DG [8].

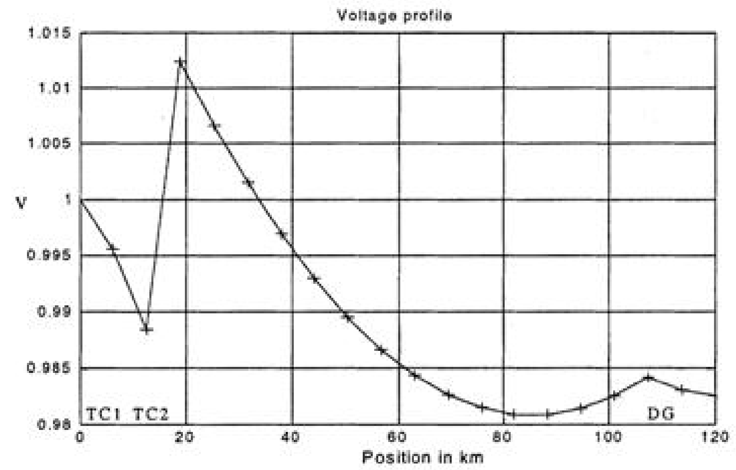

Figure 2.7: Voltage profile with 352kW load and 100kVA DG [8].

2.5 Investigation of existing SWER monitoring techniques

Through consultation with Energy utilities, it has been found so far that no monitoring of SWER infrastructure exists past the first recloser. While there is data collected off HV and MV three phase transmission systems, predominantly at substation level, line monitoring in these systems is also limited. Only one Utility reported having knowledge of monitoring on a SWER recloser (directly after the isolation transformer), and this was a single instance.

All Utilities felt it would be highly advantageous to implement monitoring on SWER systems, as many are now involved in creating a three phase distribution monitoring network to increase visibility of the system. Country Energy stated they are currently increasing their GSM monitoring of network reclosers through the entire distribution network from eighteen hundred to approximately four thousand over the next few years. Their concern for SWER systems is the lack of GSM network availability in remote and rural areas.

2.6 Conclusion

SWER systems are created to supply geographically dispersed customer bases that cannot be serviced by traditional three phase methods due to cost constraints. Additionally, SWER systems are required to be technologically robust and operationally flexible to meet the multitude of environmental operating conditions they are deployed in.

Long conductor lengths of cheaper, higher resistance conductors create voltage stability issues under both light and heavy load conditions. Line charging currents can exceed isolation transformer ratings in larger systems, providing distribution problems for utilities. Increasingly, poor power quality is the net result for customers connected to SWER systems. Static shunt inductors have alleviated the over voltage problems historically, but now contribute to the under voltage problems being faced with higher customer power demands.

The issues raised by the proposal of adding DG, LVR's, smart OLTC's and dynamic shunt controllers to SWER networks has been considered in isolation to any general knowledge of the network outside the immediate vicinity of the connecting device. Should a comprehensive evaluation of the networks status be available, from the isolation transformer to load elements to augmentation availability, a more effective and efficient management scheme may be implemented. If centralised management of these technologies could be achieved, including line and equipment fault diagnosis, SWER networks would enter a new era of unprecedented service provision.

3 Introduction to Smart Networks

The term *Smart Network* is being used to encompass ideological changes to the way in which power will be generated, distributed and consumed in the future. Distribution may be via intelligent networks that are self healing, support communications and provide utilities with real time network environmental data.

Historically, the efficiencies of cost verses scale have dominated how power systems were designed and built. With a nominal life span of forty years, much of the infrastructure currently providing power across Europe is reaching the end of its life cycle. Additionally, it is supporting load growth beyond the forecast levels predicted at the time of design [18]. In Australia, the majority of our transmission infrastructure has been in constant use for over thirty years and will require significant capacity enhancements or replacement over the next ten years [19].

In 2006, the European Commissions Green Paper *"A European Strategy for Sustainable, Competitive and Secure Energy"* laid out a blueprint for realising smart networks. Key concepts for moving forward were listed as [20];

- Flexible: fulfilling customers needs whilst responding to the changes and challenges ahead;
- Accessible: granting connection access to all network users, particularly for renewable power sources and high efficiency local generation with zero or low carbon emissions;
- Reliable: assuring and improving security and quality of supply, consistent with the demands of the digital age with resilience to hazards and uncertainties;
- Economic: providing best value through innovation, efficient energy management and level playing field competition and regulation.

While the ideology of smart networks has the potential to revolutionise the way in which generation companies, utilities and consumers interact, the physical constraints of the current system coupled with still growing demand will ensure a closely run race between short term investment in current technologies and long term investment in the smart networks of the future.

3.1 The Smart Network paradigm

In implementing a smart network, balance for the system stakeholders must be achieved. Previous thinking limited these to financial inputs (paying customers, generation resource and distribution infrastructure costs). With growing global concern on environmental disturbances resulting from energy generation and use, new stakeholders are being acknowledged. Figure 3.1 [20] presents the inputs for a balanced smart network in accordance with the European Commissions 2006 Green Paper.

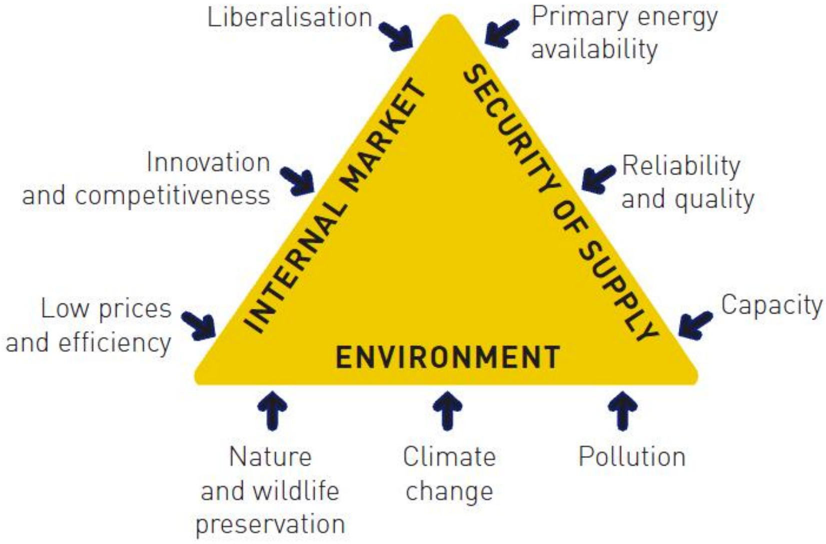

Figure 3.1: Inputs to a balanced power distribution system [20]

Smart networks are expected to have a number of core enabling technologies [20]. Utilising existing technologies from other sectors (e.g. telecommunications and Information Technology) will assist efforts in the development of new technologies specific to aspects of power generation, delivery and usage. These new technologies as listed in [20] will include;

- Active distribution networks, revealing characteristics of today's transmission grids;

- New network technologies that facilitate increased power transfers and loss reduction;
- Wide deployment of communications to enable grid automation, on-line services, active operation, demand response and demand side management;
- Power electronic technologies for quality of supply;
- Stationary energy storage devices. Combined Heat and Power Households, Industrial and commercial Wind farms

The role of communication in smart networks, as stated above, is multifaceted. For the delivery of some services (broadband Internet, telephony etc), there is a large bandwidth requirement. Other services such as active operation and demand site management can operate over more restricted bandwidths if required. Currently, any services provided would be through a third party communications network, however the area of powerline communications (PLC) research is now making inroads into using the distribution system itself as the communications medium.

3.2 Defining Power Line Communication

PLC has been used since the 1950s for relay remote control of infrastructure such as town lighting. Control units detect low frequency (10 Hz) signals for two state operation, switch on, switch off. Research into using the grid for one way signalling at higher bandwidths (5-500 kHz) began in the mid 1980s [21]. Current implementations of streetlight control systems using PLC are bi-directional, and have seen streetlight associated cost reductions of almost 50% in U.K and Norwegian cities [22].

The frequency spectrum of PLC is a contentious issue globally. Australia's communications authority, the ACA, have so far adopted both the European and U.S standards for narrowband transmission over power lines between 3 kHz and 525 kHz [23]. CENELEC EN 50065-1 (Table 3.1) provides the structure for bandwidth allocation between 9 kHz and 145 kHz for Europe while the U.S standard IEC 61000-3-8 allows use of the entire spectrum for low voltage home and utility applications.

Currently, the ACA has no standard for PLC above 525 kHz [23].

Broadband power line services (BPL) typically occupy the frequency range between .5 and 30 MHz. While nominal data rates of 2 Mbps are now common, data rates over

Table 3.1: CENELEC bands for powerline communications [24]

Band	Frequency range (kHz)	Max. Transmission amplitude (V)	User dedication
A	9-95	10	Utilities
B	95-125	1.2	Home
C	125-140	1.2	Home

short distances of up to 40 Mbps have been prototyped by some manufacturers [24]. The technology is primarily deployed to interconnect local area networks between buildings and provide network access within homes and offices to a gateway device [24].

Currently there are no specific standards for BPL but the *HomePlug Powerline Alliance* was formed in march 2000 to provide a forum from which an open standard could be developed [25]. The IEEE P1901 Working Group is yet to complete the standard for BPL networks, however proposals by HomePlug have been approved for inclusion as the baseline for an IEEE powerline communications standard [26].

3.3 Current PLC issues

Limiting factors for BPL are electromagnetic interference (EMI) and the high signal attenuation rates of power lines at these frequencies [24]. This area of spectrum (medium to high frequency) is used in Australia for a range of wireless services by military, aeronautical, maritime and civilian groups. Technologies range from surface wave radar to high frequency (HF) radio broadcast to cordless phones [27]. Strong opposition from current spectrum users exists as their is no direct standard associated with Electromagnetic Compatibility (EMC) levels for BPL technologies although sections of the Radiocommunications Act make it illegal for individuals or companies in Australia to create EMI capable of interfering with military, police and emergency services communications [27].

While the issues of EMI and EMC exist for narrowband PLC, the spectrum used does not compete directly with common wireless dependant technologies. The main considerations in this investigation for the use of narrowband PLC in creating a smart SWER network is the achievable data rate and signal attenuation due to line characteristics.

3.4 Conclusion

As an enabling technology for smart networks, PLC provides a communications channel that is cheap, robust and accessible. The lack of current standards coupled with EMI and EMC issues pose problems, but continued research into both broad and narrowband transmission of information along power lines may provide solutions making them a preferred carrier. Current research is mainly focused on provision of last mile broadband, as this would provide an immediate benefit to the most customers. With the global interest in SmartGrid accelerating however, research into communication over medium and high voltage transmission systems is increasing with a view to better network infrastructure management. This is particularly relevant in SWER environments, where networks cover considerable areas with no infrastructure visibility.

4 Applicability of PLC over SWER.

4.1 Advantages of a Smart SWER network

SWER networks can benefit from smart network devices on many levels. Basic line and infrastructure monitoring will provide a new level of system visibility and fault diagnosis capability, remote meter reading can be achieved, and, centralised management of smart devices can be provided by a single resource external to the system.

The complete implementation of a Smart Network will need to provide the inherent robustness of an unmanaged system while achieving the core attributes of a managed system, increased capacity, flexibility and availability. Structuring fail safe conditions of smart devices to provide stable, independent operation when in communication failure is part of the challenge facing smart networks, both in SWER and general transmission systems. For Smart SWER to be realised, the positive outcomes for the system as a whole must outweigh the added complexities of its implementation.

Historically, solutions to SWER system issues have been static in nature. Now, in trialling line voltage regulators [16] Figure 2.4 and switched reactors [28] Figure 4.2 to address system voltage and capacity concerns, utilities are beginning to make inroads into SWER power quality issues using dynamic devices.

At present, these devices operate independently of each other, adjusting their immediate environments to produce a desired outcome. As the number of these devices grows, overall network stability and control will become more complex. At some critical juncture, the network may be best managed by a central resource that constantly monitors network parameters through all points of the system. By knowing and adjusting controllable resources, the network could optimise segments for localised load requirements, utilise distributed generation where available and report

Figure 4.1: LVR installed on a SWER [7]

on network health and stability, all transparent to customers and the distribution feeder.

Figure 4.2: Thyristor Controlled Reactor trial at Stanage Bay, Central Queensland, in 2007. [6]

To facilitate communications between smart network devices and a centralised control system, a cost efficient yet robust communication channel needs to be established. Providing this channel via the distribution line itself has the advantage that no third party or independently managed services are required.

Smart network devices can provide information continuously that will help change the core power delivery mechanism from being reactive to a proactive dynamic system. As data collection improves, predictive algorithms forecasting distribution bottlenecks and potential failure points can be refined to adapt to any number of external variables.

4.2 SWER line characteristics for PLC

Power distribution systems are designed to optimally transfer energy at 50 Hz. At higher frequencies, skin effect begins to dominate the resistance parameter R in the lines characteristic equations which describe a signals propagation through it. At frequency f for a cable of radius r , the AC resistance R is given by Equation 4.1, where μ_0 is the permeability of free space and κ , the conductivity of the cable [24].

$$R = \sqrt{\frac{\pi \mu_0 f}{\kappa r^2}} \tag{4.1}$$

Assuming a single transmission line with white Gaussian noise (WGN) and ignoring multipath effects, the signal power decreases as a function of distance from the transmitter as illustrated in Figure 4.3.

The rate of attenuation is determined by the lines propagation constant γ (Equation 4.2) and characteristic impedance Z_C (Equation 4.3) [24]. α and β are known as the attenuation and phase constants for the line while R, G, L, C are the resistance, admittance, inductance and capacitance of the line respectively.

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \tag{4.2}$$

$$Z_C = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \tag{4.3}$$

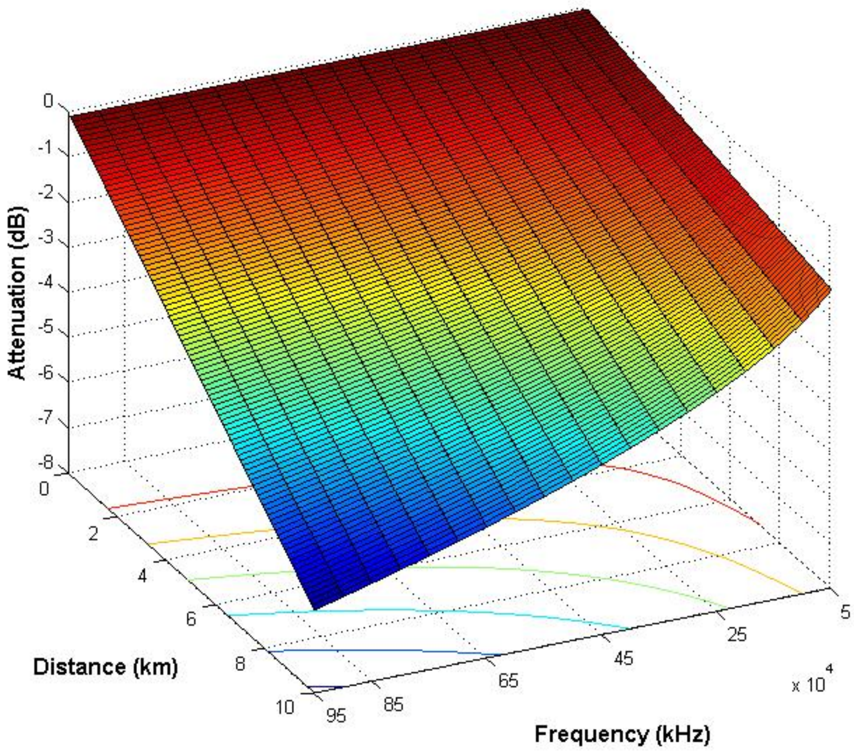

Figure 4.3: Attenuation over distance for CENELEC bandwidth

SWER transmission line characteristics differ from standard systems in 2 key areas. The shunt admittance G is generally ignored due to the distance between the line and effective return path (twice the distance between cable and ground) and the lines resistance parameter is much higher, a result of cable selection to allow greater distances between poles. As such, using Equation 4.1 and DeMoivre's theorem with $\omega = 2\pi f$, the attenuation α for a SWER environment can be approximated as

$$\alpha = \frac{1}{\sqrt{2}}\sqrt{\sqrt{(\omega^2 LC)^2 + (\omega\sqrt{\frac{\omega\mu_0}{2\kappa r^2}}C)^2} + \omega^2 LC} \tag{4.4}$$

4.3 SWER Channel Capacity

Data transfer on a transmission line is measured in bits per second (bps). The effective signaling rate however, is measured in symbols per second, or baud rate. The capacity for a receiver to differentiate between multiple amplitude, frequency or phase change levels in a transmitted signal is primarily dependent on the systems signal to noise ratio [29]. As such, the capacity of a communications channel over any medium is restricted by the effects of additive noise, interference, propagation and distortion. The Hartley-Shannon theorem (Equation 4.5) provides the inter-relationships between the channels capacity C in bits per second, bandwidth B (in Hz) and the net signal to noise ratio (SNR) resulting from the channels restricting elements [29].

$$C = B\ log_2(1 + \frac{S}{N}) \tag{4.5}$$

Figure 4.4 shows the increase in channel capacity for the increase in signal to noise ratio (in dB) for a system with 86 kHz bandwidth (CENELEC standard - Table 3.1).

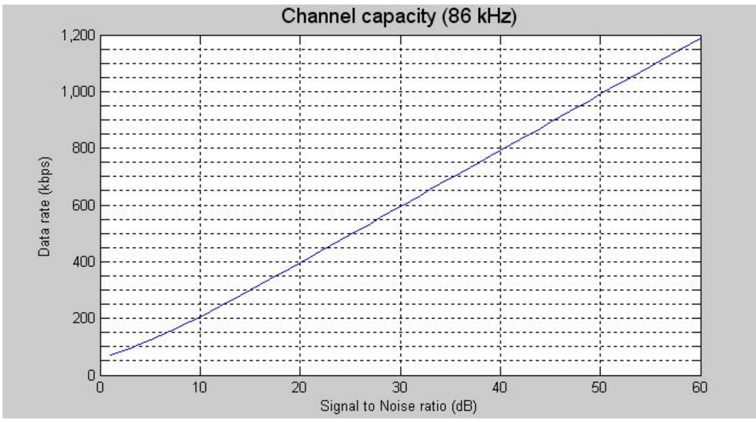

Figure 4.4: CENELEC Channel capacity

The channel capacity for a SWER line can now be found for a given noise, cable characteristic and distance *d* from the transmitter using the Hartley-Shannon theorem and the lines attenuation constant (Equation 4.5 and Equation 4.4).

$$C = B\ log_2(1 + \frac{Se^{-\alpha d}}{N}) \tag{4.6}$$

Typical SWER system conductor parameters at 50 Hz (Table 2.1) as given by Wolfs in [28] are used in Figure 4.5 and Figure 4.6 to calculate channel capacity plots for Backbone and Tee off conductors respectively over a distance of 10 km.

The reduction in channel capacity over the bandwidth, illustrated by Figure 4.5 for

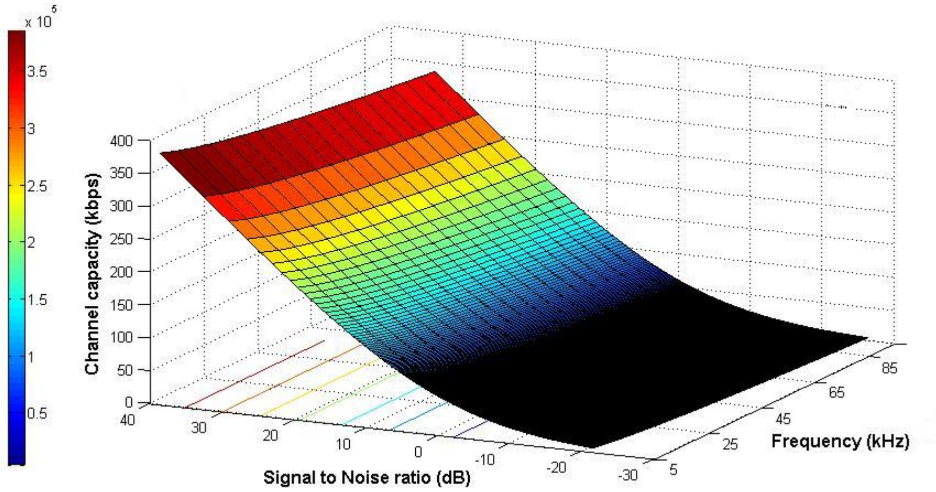

Figure 4.5: Backbone Channel Capacity at 10 km

Backbone conductor, is slight (46.4 kbps) in comparison to the Tee off conductor, (249.9 kbps, Figure 4.6) at an SNR of 20 dB.

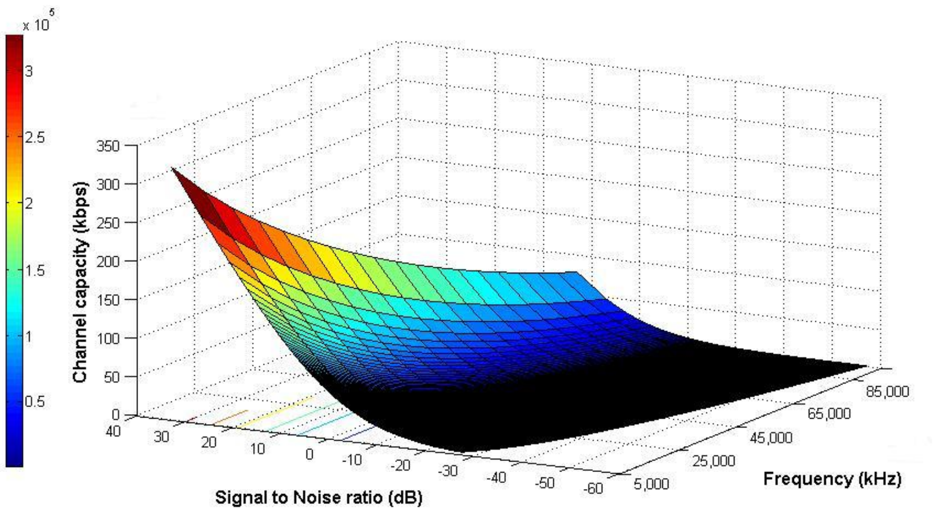

Figure 4.6: Tee Off Channel Capacity at 10 km

This is largely the result of skin effect exhibited by the Tee off conductor as a function of its conductivity κ .

Table 4.1 compares the channel capacity calculated at specific noise levels over a range of distances. A central frequency of 50 kHz is used in these calculations along with Backbone conductor characteristics.

Table 4.1: Calculated channel capacity variation over distance

	-30dB	-15dB	-5dB	0dB
1 km	295.42$kbps$	1.5885$kbps$	85.07$kbps$	57.43$kbps$
10 km	257.21$kbps$	1.2666$kbps$	62.27$kbps$	40.30$kbps$
50 km	105.57$kbps$	30.70$kbps$	10.94$kbps$	6.32$kbps$
100 km	14.53$kbps$	2.77$kbps$	0.89$kbps$	0.5$kbps$

Noise power is calculated relative to the CENELEC maximum transmission amplitude of 10V for utility use at the transmitter while the SNR at the indicated distances incorporates the attenuation constant α as per Equation 4.4. The near linear attenuation over distance described in Table 4.1 is consistent over the entire transmission spectrum.

4.4 Conclusion

A smart SWER network can provide benefits to utilities previously unseen. Network monitoring, fault diagnosis and control of smart network infrastructure would become tools for optimising a networks efficiency and throughput. These tools can only be utilised if an appropriate communications channel exists along which system information can flow.

To use the SWER network as this channel, the channel capacity given typical SWER backbone and tee off conductor parameters needed to be verified. section 4.2 and section 4.3 examined the the characteristics of conductors and established a channel capacity for conductor types relative to a predetermined noise level. This analysis provides a degree of confidence in the worth of further investigating PLC over SWER.

5 Network modeling and multipath effects

5.1 Introduction

To date, there has been no assessment of the capability of SWER networks to support communication as a mechanism for network monitoring. This research will provide the basis for the provision of communications infrastructure via the SWER transmission system, assisting in the extension of SmartGrid technologies and dynamic power quality support devices into the SWER environment.

5.2 Multipath communication systems

While the calculated channel capacity for Backbone and Tee off conductors is considerably different, seen when comparing Figure 4.5 and Figure 4.6, both may support data rates appropriate for their purpose of deployment. Tee off, typically used to feed several customers as a maximum, could support 50 kbps data rates at a 20 dB SNR over 10 km, sufficient for 5 RTU's at 9600 bps, a common data rate for SCADA remote monitoring. The calculated channel capacity for Backbone conductor is much higher, allowing for data rates of several hundred kbps which would be required for data agrigation points. From this study, it can be seen PLC over SWER infrastructure is feasible and may support adequate data rates for system monitoring and fault diagnosis.

5.3 Channel noise

The types of, and energy contained within additive noise and interference for SWER systems is currently an unknown for SWER PLC and requires further investigation. The noise levels used in Sections section 4.2 and section 4.3 calculations are consistent with levels used in measuring performance of basic modulation schemes. An investigation into the characterisation of noise types for SWER systems will include background, coloured background, narrowband and impulsive noise. These will form the interference basis for a comprehensive channel model.

5.4 SWER multipath analysis

The assumption of no multipath interference in Section section 4.2 is made to simplify the assessment of channel capacity. Multipath effects are the result of signal reflections produced when impedance changes occur in the transmission medium. Line branches, equipment connections, cable joints are all sources of multipath reflections. This study will characterise reflection coefficients for given impedance change parameters and analyse the effects on signal attenuation that result for SWER systems. Again, this analysis is key to creating a comprehensive channel model.

5.5 Channel model for SWER transmission systems

The project aims to provide a realisation of a novel SWER channel model for future SWER PLC investigations that can be applied to the many topological SWER network variations that exist. An in depth physical description of SWER parameters will be derived to ensure accuracy. It will take into account noise properties associated with SWER conductors, additive noise associated with the SWER environment and common loads as well as the attenuation of signals due to both multipath effects and characteristics of conductors in SWER systems.

5.6 Conclusion

While SWER distribution systems operate on the fringe of the current grid, they cover over 190 000 km [16] of Australia's regional areas. With a current estimated value of several billion dollars [16], augmentation of the systems capacity to support growing rural demand is not viable. More efficient management however, using a SmartGrid paradigm, may provide sufficient capacity and quality of service to extend the life of the current network while assisting in augmentation planning through greater network visibility.

Investigation of communications systems requires a thorough understanding of the transmission medium. Signal attenuation and noise factors effect the rate of information flow and need to be considered for any system design. The characterisation of the transmission medium is referred to as the transmission channel model. As communications is a critical component of a SmartGrid implementation, this project aims to produce a channel model for SWER networks that can be used in the design, analysis and testing of future communications infrastructure models, required for the realisation of smart SWER.

6 Conclusion and further research

6.1 Introduction

To date, there has been no assessment of the capability of SWER networks to support communication as a mechanism for network monitoring. This research will provide the basis for the provision of communications infrastructure via the SWER transmission system, assisting in the extension of SmartGrid technologies and dynamic power quality support devices into the SWER environment.

6.2 Validation of SWER PLC capacity

While the calculated channel capacity for Backbone and Tee off conductors is considerably different, seen when comparing Figure 4.5 and Figure 4.6, both may support data rates appropriate for their purpose of deployment. Tee off, typically used to feed several customers as a maximum, could support 50 kbps data rates at a 20 dB SNR over 10 km, sufficient for 5 RTU's at 9600 bps, a common data rate for SCADA remote monitoring. The calculated channel capacity for Backbone conductor is much higher, allowing for data rates of several hundred kbps which would be required for data agrigation points. From this study, it can be seen PLC over SWER infrastructure is feasible and may support adequate data rates for system monitoring and fault diagnosis.

6.3 Channel noise investigation

The types of, and energy contained within additive noise and interference for SWER systems is currently an unknown for SWER PLC and requires further investigation.

The noise levels used in Sections section 4.2 and section 4.3 calculations are consistent with levels used in measuring performance of basic modulation schemes. An investigation into the characterisation of noise types for SWER systems will include background, coloured background, narrowband and impulsive noise. These will form the interference basis for a comprehensive channel model.

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6.6 Further research

An assessment of current modulation schemes for power lines and their applicability of use in the SWER environment relative to the channel characteristics will be included as an introduction to future research required to enable the implementation of PLC over the SWER environment. This assessment will include amplitude, phase and frequency modulation schemes, including orthogonal frequency division multiplexing (OFDM), a technique being used in the implementation of three phase system communications modems.

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Nomenclature

μ_0	permeability of free space
κ	conductivity
ACA	Australian Communications Authority
BPL	Broadband Power Line
CENELEC	European Committee for Electrotechnical Standardization
DG	Distributed generation
DG	Distributed generation
EMC	Electromagnetic Compatibility
EMI	ElectromagneticInterference
f	Frequency
GSM	Global System for Mobile Communications
kbps	kilo bits per second
kHz	kilohertz or thousands of cycles per second
LVR	Line Voltage Regulator
Mbps	Mega bits per second
MHz	Mega Hertz - millions of cycles per second
OLTC	On-Load Tap Changer
PLC	Power Line Communication

SNR Signal to Noise Ratio

SWER Single Wire Earth Return

TCR Thyristor Controlled Reactor

VARS Reactive Power or Volt Amp Reactive

WGN White Gaussian Noise

X/R reactance to resistance