Monitoring of Single Wire Earth Return systems using Power Line Communication

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***Abstract*—As demand for power increases in rural areas serviced by Single Wire Earth Return (SWER) networks, distribution issues are becoming increasingly evident. Voltage regulation and system capacity concerns are driving utilities toward using smarter compensation devices for network control in an attempt to provide longevity for aging SWER infrastructure. To date, despite increasing complexity in power delivery over SWER, no effective network monitoring solutions have been proposed.**

This paper examines the case for network monitoring and centralised management of smart compensation devices via Power Line Communications (PLC). After establishing advantages in network monitoring, regulation and maintenance for SWER networks, narrowband and broadband PLC issues are reviewed. The channel capacity of typical SWER conductors is then evaluated and compared to data throughput requirements derived from existing infrastructure to validate the applicability of developing PLC over SWER infrastructure.

I. INTRODUCTION

Historically, solutions to SWER system issues have been static in nature. Now, in trialling line voltage regulators [1] and switched reactors [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.

Fig. 1. LVR installed on a SWER [1]

At some critical juncture, the network will be best managed by a central resource that constantly monitors network parameters through all points of the system.

Fig. 2. Thyristor Controlled Reactor trial at Stanage Bay, Central Queensland, in 2007. [13]

By knowing and adjusting controllable resources, the network could optimise segments for localised load requirements, utilise distributed generation where available and report on network health, all transparent to customers and the distribution feeder.

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

II. SMART GRIDS

The concept of a *Smart Grid* is being developed globally as an enabling technology for efficient and flexible power delivery. While its exact definition varies widely, its advantages are hoped to include [3]:

- Greater consumer participation in energy markets,
- The accommodation of distributed generation and storage technologies,
- Provision of new services to customers,
- Optimisation of asset utilisation and operational efficiencies.

This list is by no means extensive, and power utilities have individual needs that only encompass small areas in a Smart

Grids potential. In the delivery of power, areas of interest facilitated by a Smart Grid includes [4]

- Real-time simulation and contingency analysis,
- Self healing networks,
- Asset management
- Real time equipment monitoring.

One realisation of the last point is real time network management and fault diagnosis using communications enabled infrastructure. 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.

While SWER distribution systems operate on the fringe of the current grid, they cover over 190 000 km [1] of Australia's regional areas. With a current estimated value of several billion dollars [1], augmentation of the systems capacity to support growing rural demand is not viable. More efficient management however, using a Smart Grid 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.

III. POWER LINE COMMUNICATIONS

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 [5]. 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 [6].

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 [7]. CENELEC EN 50065-1 (Table I) 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 [7].

TABLE I
CENELEC BANDS FOR POWERLINE COMMUNICATIONS [8]

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

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 short distances of up to 40 Mbps have been prototyped by some manufacturers [8]. The technology is primarily deployed to interconnect local area networks between buildings and provide network access within homes and offices to a gateway device [8].

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 [9]. 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 [10].

Limiting factors for BPL are electromagnetic interference (EMI) and the high signal attenuation rates of power lines at these frequencies [8]. 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 HF radio broadcast to cordless phones [11]. 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 to create EMI capable of interfering with military, police and emergency services communications [11].

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 for the use of narrowband PLC in creating a smart SWER network is the achievable data rate and signal attenuation due to line characteristics.

IV. SWER CHANNEL CAPACITY

Data transfer on a transmission line is measured in bits per second (bps). The effective signalling 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 dependant on the systems signal to noise ratio [12]. 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 1) 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 [12].

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

Figure 3 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 I).

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

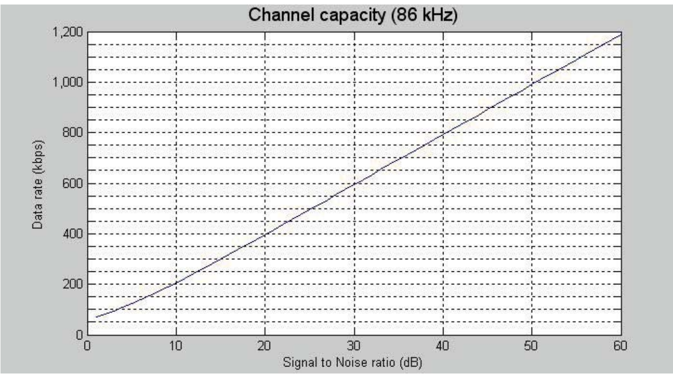

Fig. 3. CENELEC Channel capacity

frequency f for a cable of radius r, the AC resistance R is given by Equation 2, where μ_0 is the permeability of free space and κ, the conductivity of the cable [8].

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

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. The rate of attenuation is determined by the lines propagation constant γ (Equation 3) and characteristic impedance Z_C (Equation 4) [8]. 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.

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \tag{3}$$

$$Z_C = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \tag{4}$$

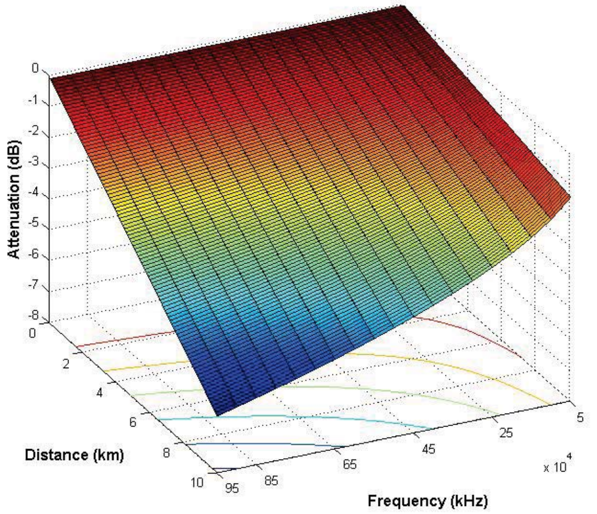

Fig. 4. Attenuation over distance for CENELEC bandwidth

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 2 and DeMoivre's theorem with $\omega = 2\pi f$, α for a SWER environment can be approximated as

$$\alpha = \frac{1}{\sqrt{2}}\sqrt{\sqrt{(\omega^2 LC)^2 + (\omega\sqrt{\frac{\omega\mu_0}{2\kappa r^2}}C)^2} + \omega^2 LC} \tag{5}$$

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 (Equation 1 and Equation 5).

$$C = B\ log_2(1 + \frac{Se^{-\alpha d}}{N}) \tag{6}$$

TABLE II
SWER CONDUCTOR PROPERTIES AT 50HZ [13]

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

Typical SWER system conductor parameters at 50 Hz (Table II) as given by Wolfs in [13] are used in Figures 5 and 6 to calculate channel capacity plots for Backbone and Tee off conductors respectively over a distance of 10 km.

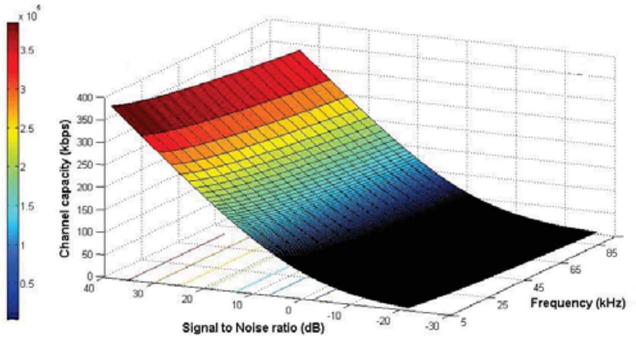

Fig. 5. Backbone Channel Capacity at 10 km

The reduction in channel capacity over the bandwidth, illustrated by Figure 5 for Backbone conductor, is slight (46.4 kbps) in comparison to the Tee off conductor, (249.9 kbps, Figure 6) at an SNR of 20 dB.

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

Table III 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. Noise power is calculated relative to the CENELEC maximum transmission amplitude of 10V for

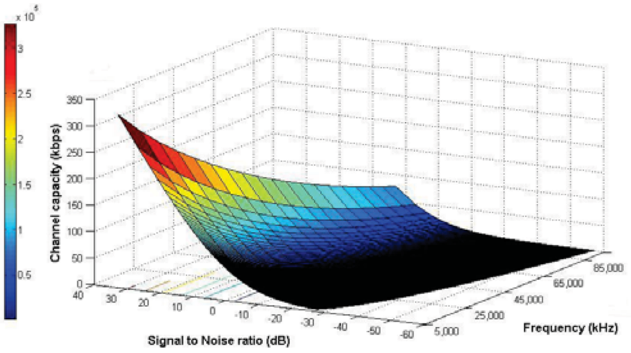

Fig. 6. Tee Off Channel Capacity at 10 km

TABLE III
CHANNEL CAPACITY VARIATION OVER DISTANCE

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

utility use at the transmitter while the SNR at the indicated distances incorporates the attenuation constant α as per Equation 5. The near linear attenuation over distance described in Table III is consistent over the entire transmission spectrum.

V. PLC OVER SWER

The data rate from each reporting device in a smart network has 2 dependencies, the message size and the frequency of reporting. Standardisation of control signal messaging protocols (IEC 61850) and the advent of TCP/IP is seeing utilities move from peer to peer networks based on the RS232 serial protocol with data rates of 1200 to 19200 bps to broadband services provided via microwave, satellite and fibre optic carriers. The overhead of TCP/IP (minimum of a 54 byte packet) [12] in sending a single figure byte message is no longer an issue at higher bandwidths. Additionally, reporting rates can be increased to provide real time reporting for system or device status.

SWER networks vary greatly in their geographical and physical structure from simple feeds of several kilometres servicing 2 or 3 customers to the complexity of the Jericho North network shown in Figure 7. Given the cost of deploying any communications infrastructure that had to include a separate communications channel and SWER's inherent robustness, little or no continuous system monitoring has been attempted to date. As such, effective data rates for real time reporting on SWER networks has yet to be established while preserving the primary consideration of a SWER deployment, cost.

At time of writing [13], Jericho North contained 43 customer transformers and nine 25kVAr shunt reactors over a total line length of 364 km. The conductor parameters (given in Table II) are typical of SWER networks, usually fed via an isolation transformer from two phases of a 22kV (12.7kV SWER) or 33kV (19.1kV SWER) three phase transmission system. A backbone conductor is run through the general demand area with tee off's used to service individual or small clusters of customers.

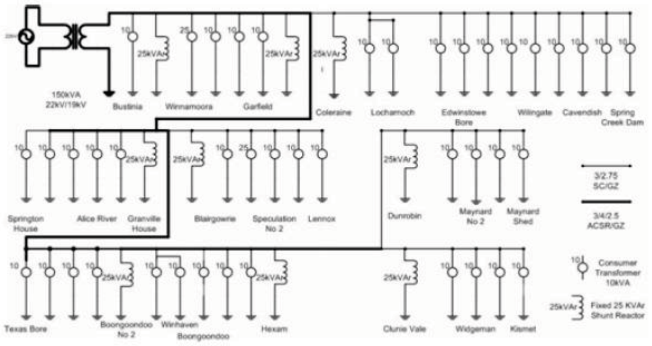

Fig. 7. The Jericho North system [13]

Using Jericho North as an example of a large SWER system and assuming each customer and shunt device on the network is smart enabled, 53 devices would be communicating over the transmission channel (including the isolation transformer). Given that Supervisory Control and Data Acquisition (SCADA) systems currently in use by utilities deploy Remote Terminal Units (RTU's) with 9600 bps rates for equipment monitoring, a SWER line channel capacity of around 500 kbps (53 units x 9600 bps) would be required at the gateway device for the Jericho North network.

Current modem technologies deployed in the narrowband PLC market are aimed at the Automatic Meter Reading (AMR) and Automatic Meter Management (AMM) infrastructure being rolled out globaly, as well as equipment and system monitoring. Companies report [14] good data throughput using Orthogonal Frequency Division Multiplexing (OFDM) modulation schemes and TCP/IP with signal attenuations of up to 86 dB for CENELEC frequencies.

VI. CONCLUSION

This paper aimed to demonstrate the capacity of SWER systems to support PLC as an effective and efficient means of providing system monitoring. The channel characteristics of typical SWER conductors were used to evaluate frequency dependant signal attenuation over distances common in SWER networks. A changing noise gradient was applied to these calculations providing an indicative channel capacity for SWER conductors.

While the calculated channel capacity for Backbone and Tee off conductors is considerably different, seen when comparing Figures 5 and 6, both will 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. 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.

The types of, and energy contained within addative noise and interference for SWER systems is currently an unknown for SWER PLC and requires further investigation. The noise levels used in this paper's calculations are consistent with levels discussed in the cited references for a range of PLC modulation schemes. The assumption of no multipath interference is made to simplify the assesment of channel capacity. Future work will asses the implications of this when a more complete channel model is created. It should also be noted, the high attenuation rates found in SWER conductors could be used when designing modem/repeaters for SWER netorks as a natural topolocial barrier to data retransmission.

REFERENCES

[1] J.Turner and G.S. Ivanovich , *"Low Voltage Regulators - A New Device for Voltage Quality Improvement"*, Transmission and Distribution, issue: August/September pp 74-77, APT Publications, 2008.

[2] P.J. Wolfs, J. Turner, N. Hosseinzadeh and M. Hesamzadeh *"Capacity Enhancements with Switched Reactors"*, Transmission and Distribution, issue: August/September pp 78-79, APT Publications, 2008.

[3] E. Lightner and R. Scheer, *"Transforming the grid"*, Electric Perspectives, November/December 2008, Available at: http://www.energetics.com/features.asp?Feature=91, Viewed 5rd April 2009.

[4] de Laeter, M, *"The Smart Grid"*, Presentation to API Residential School by Western Power, Available at: http://en.kioskea.net/contents/cpl/cpl-intro.php3

[5] Franoise Cacciaguerra, *"Introduction to power line communications (PLC)"*, Available at: http://en.kioskea.net/contents/cpl/cpl-intro.php3

[6] SungKwan Cho and Dhingra, Vijay, *"Street lighting control based on LonWorks power line communication"* Power Line Communications and Its Applications, 2008. ISPLC 2008. IEEE International Symposium on, pp.396-398, 2-4 April, 2008.

[7] Spectrum Planning Team Document Radiofrequency Planning Group, *"Broadband Powerline Communications Systems - A Background Brief"*, Australian Communications Authority, September 2003, Available at: http://www.acma.gov.au/webwr/radcomm/frequency_planning /spps/0311spp.pdf

[8] H. Hrasnica, A. Haidine, R. Lehnert, *"Broadband Powerline Communications Networks - Network Design"*, John Wiley & Sons, 2005

[9] K. Dostert, *"Powerline Communications"*, Prentice Hall, 2001

[10] IEEE Report *"IEEE P1901 Draft Standard for Broadband over Power Line Networks: Medium Access Control and Physical Layer Specifications"*, Report on the meeting held in Kyoto, Japan, 16-19 December 2008. Available at: http://grouper.ieee.org/groups/1901/

[11] BPL Project Team, *"The Management of Interference from Broadband over Power Line Applications"*, Australian Communications Authority, April 2005, Available at: http://www.acma.gov.au/webwr/lib284/bpl discussion paper _electronic version_.pdf, Viewed 3rd April 2009.

[12] F. G. Stremler, *"Introduction to Communication Systems"*, Addison-Wesley Publishing Company, 3rd Edtion, 1990.

[13] P.J.Wolfs, N.Hosseinzadeh, S.T. Senini, *"Capacity Enhancement for Aging Single Wire Earth Return Distribution Systems"*, IEEE Power Engineering Society General Meeting, 2007, 24-28 June 2007, pp 1 8.

[14] Cipunet, *"Ethernet PLC-Modem CMM2500"*, Available at: http://www.cipunet.de/index.php?page=ethernet-hf-modem