Modeling Power Transformers for the Design of SWER Line Coupling Networks.

C. J. Kikkert
School of Engineering and Physical Sciences,
James Cook University
Townsville, Queensland, Australia, 4811

Abstract— **Many countries use Single Wire Earth Return Power (SWER) lines for providing power to customers in rural areas. These SWER lines can be up to 300 km long. For Smart Grid applications and power quality assurance on SWER lines, a communication system is required. Power Line Communications (PLC) signals in the 9 to 95 kHz CENELEC-A frequency band are the most economical means for providing this communication on SWER lines. To inject the PLC signals on the typical 19.1 kV SWER line, a low cost coupler is required. The behavior of SWER line power transformers at PLC frequencies is critical for the design of this coupling network.**

This paper describes the development of a wide frequency band model for SWER line power transformers and uses this model for the design of coupler networks. A novel technique is used to match the transformer model to measurements. This model matching technique and the resulting transformer model are also applicable to other power transformers.

I. INTRODUCTION

In Australia, USA, South Africa and many other countries, power to remote communities is provided by Single Wire Earth Return (SWER) lines. Such power lines can be up to 300 km long. It is highly desirable to be able to use smart grid techniques to read the customer's electricity meter remotely, since a 600 km trip on dirt roads costs more than the electricity charge.

One option for a smart grid communication system is to use PLC signals in the CENELEC A frequency band from 9 kHz to 95 kHz, which is set aside for use by Power Supply Companies, the other option is to use a radio system. However, for the majority of these customers no cell phone coverage is available. Satellite phones are too expensive to operate, so that the use of PLC is highly desirable for Smart Grid applications on the SWER lines.

The SNR of a PLC communication system and a comparison between the customer and sending end voltage, current and power are a good monitor of the integrity of the SWER line, as arcing between the SWER line and trees or other SWER line-faults are not easily detected by other means. PLC communication is thus important for power quality assurance on SWER lines.

ERGON, the Australian electricity utility based in Queensland, has been sponsoring a research project to show that PLC signals can be used for Smart Grid communications on SWER lines. An accurate model for resistive loss and the power line radiation of any power line was developed by the JCU team and this model shows an excellent agreement with measurements on an 18km long SWER line [1]. This SWER line model shows that even for very long SWER lines, the resistive losses dominate and that the radiation at CENELEC-A frequencies is very small and unlikely to cause any detectable interference to other users. In April 2010, a 14.3 km long SWER line was isolated and MAX2290EV Development kit was used as a CENELEC-A modem at both ends of the line. The outputs from these modems were connected directly to the SWER line through a 50 Ω attenuator. A data rate of 22 kbps was obtained on this 14km line. The line has an attenuation of less than 20dB over the CENELEC-A band. The total attenuation of the 50 Ω attenuators could be increased to 15dB before the link stopped operating. This implies that with proper low loss coupling networks, communications on a Steel Core Aluminum Clad (SCAC) SWER line in excess of 100km should be possible.

As shown in this paper, the SWER-line power transformer needs to form an integral part of a low cost coupling network to couple the communication signals onto the typical 19.1 kV SWER line. This requires the development of an accurate model of the SWER-line power transformer at PLC frequencies, which is described here. This transformer model with different parameters applies conventional three phase transformers as well.

This work was supported in part by the Queensland Electricity provider ERGON.

II. TRANSFORMER MODEL

A. *Transformer Model Developments*

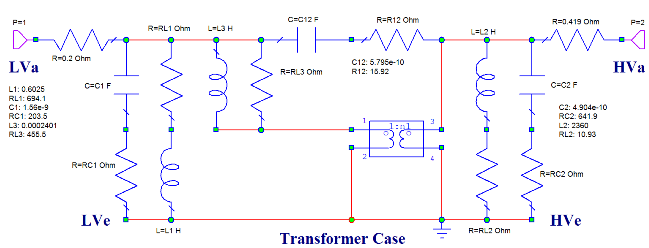

Fig. 1. Wide frequency transformer model

The power transformer can be modeled by the circuit shown in fig. 1. Joan [2] uses a similar model, but does not produce a frequency response. Other researchers [3-6] produce transformer models which do not yield a simple schematic circuit and only apply to circuit transients.

The frequency response of the magnetic core is such that the magnetic coupling ceases to function at high frequencies [2]. The magnetic coupling is included in the model as an ideal transformer, with an 83 turns-ratio to convert the 230 V low voltage (LV) to the 19.1 kV high voltage (HV) of the SWER line. In other countries the voltages and the required turns ratio will be different and this will result in different impedances for the model. The decrease in magnetic coupling with frequency is modeled by including an inductor, L3, in series with this ideal transformer. It was found a better impedance match was obtained by including a resistor RL3 in parallel with this inductor L3. At low frequency, the LV and HV windings reflect the magnetizing inductance of the transformer, which is modeled as an inductor, L1 or L2, in series with resistors, RL1 or RL2, in parallel with the ideal transformer LV and HV terminals respectively.

At high frequencies the LV and HV windings each have a capacitance associated with them, due to capacitive coupling between the coils making up the winding. This is modeled by a capacitor, C1 or C2, in series with a resistor, RC1 or RC2, representing the losses of these high frequency winding impedances. In addition, there is a capacitive coupling between the LV and HV windings, which is modeled by a capacitor, C12, in series with a resistor, R12, representing the losses associated with this coupling. Normally a lossy capacitor is modeled using a parallel RC network. It was however found that a series RC network gave a better match at PLC frequencies.

Normally 5 terminals are available on the transformer, Low Voltage Active (LVa), Low Voltage Earth (LVe), High Voltage Active (HVa), , High Voltage Earth (HVe) and the transformer case (Case). To characterize the transformer, impedance measurements are made on the following 5 terminal combinations: Port 1: LVa-LVe, Port 2: HVa-LVa, Port 3: HVa-HVe, Port 4: HVe-Case and Port 5: LVe-Case. Those measurements are then used to develop the model. During operation, the LVe and Hve terminals are connected to the transformer case using links. Several SWER transformers of different ratings were measured. Different transformers of the same rating gave very similar measurements, so that the same model can be used for the same rating SWER transformers. The different rating transformers only gave slightly different impedances, so that the same model with slightly different values can be used.

B. *Matching the model to measurements*

The problem now becomes how to match the components in the model to the impedance measurements. One could write down equations for the impedances that can be seen in each of the 5 measurement points and solve the resulting complex equations to obtain the component values. Since the measured impedances change in a complex manner with frequency, solving these equations is an exceedingly difficult task.

It is possible to use modern circuit simulation and optimization tools, to "solve" the simultaneous equations by optimization and thus matching the circuit elements in fig. 1 to the measurements. For this paper, Microwave Office (MWO) from AWR is used for the circuit simulator. Even though this software is primarily designed for RF and Microwave circuits, it can be used at any frequency and is used here to do the optimization to match the transformer model to the measurements.

Fig. 2 shows how LVa, LVe, HVa HVe and the case of the

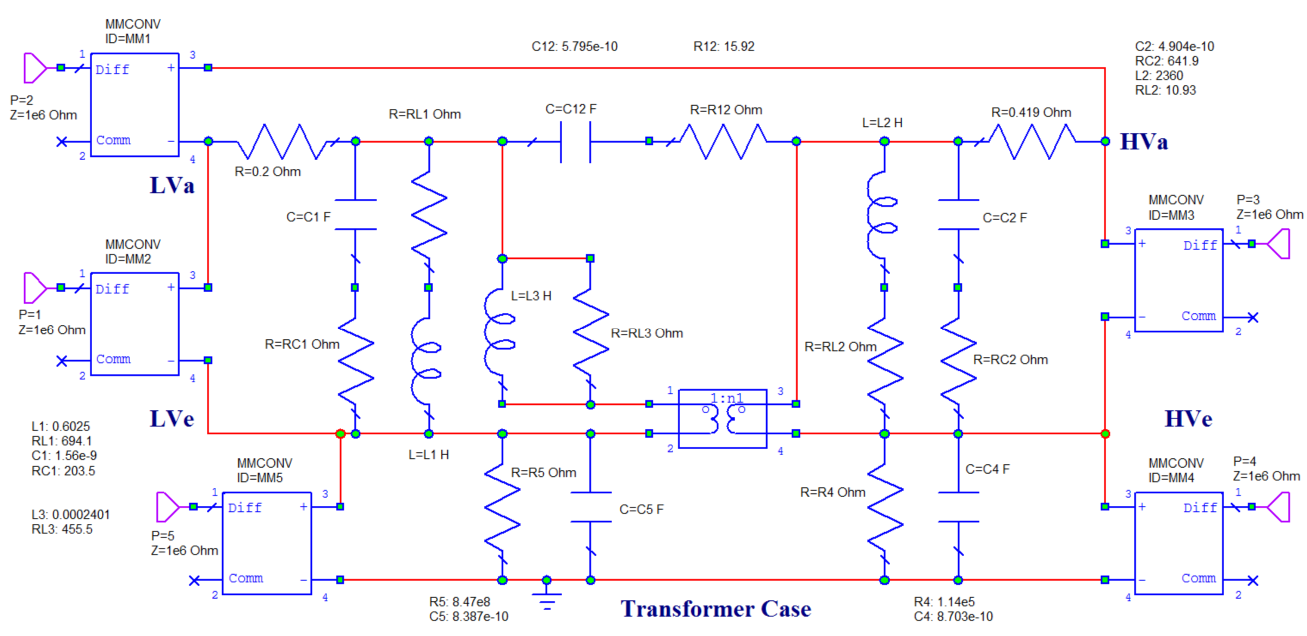

Fig.2. Transformer model impedance measurement ports

transformer model in fig. 1 are connected to MMCONV (Mixed Mode Converter) elements. These change the two-terminal connections, like LVa to LVe, to a differential mode terminal. The associated common mode terminal, is earthed as no common mode signals are injected into the transformer. The impedance looking into each of the ports is then calculated using MWO. To ensure that the other ports have negligible effect on the impedance calculations, they are terminated into a 1MΩ impedance. For port 1, the measured magnitude of the input impedance ($MeP_1Z_{11}M$) and the modeled magnitude of the input impedance ($MoP_1Z_{11}M$) are used to produce the normalized magnitude error function shown in (1). The measured phase of the input impedance ($MeP_1Z_{11}P$) and the modeled phase of the input impedance ($MoP_1Z_{11}P$) are used to produce the phase error function shown in (2).

$$EP_1Z_{11}M = \frac{MeP_1Z_{11}M - MoP_1Z_{11}M}{MeP_1Z_{11}M + MoP_1Z_{11}M + 30} \quad (1)$$

$$EP_1Z_{11}P = MeP_1Z_{11}P - MoP_1Z_{11}P \quad (2)$$

A value of 30 is included in (1) to give less weight to the error function for small impedance values. This was found to lead to a better overall model-measurement match during the optimization. Similar equations are generated for all the other ports. Each of the parameters are manually "tuned" using the tuning tools in MWO to provide initial best guesses for the component values. The circuit simulator is then set to "optimize" and make the error functions as small as possible.

Initially the optimization was carried using the Real and Imaginary parts of the port impedances, however it was found that smaller errors could be obtained by optimizing the magnitude and phase of the impedances and using a bigger weighting for the magnitude (1) than the phase (2).

C. *Measured Transformer Impedances*

Since the SWER line acts as a good AM radio antenna, significant radio signals are likely to exist on the line. To develop an accurate model of a SWER line and measure the open circuited and short circuited impedances of an 18 km SWER line, a special purpose impedance analyzer had to be constructed. This consists of a set of switched precision resistors in series with the load, whose impedance is to be determined as a simple potential divider shown in fig. 3.

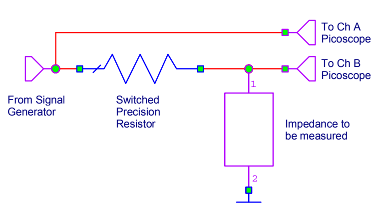

Fig. 3. Impedance Measurement Bridge

A computer controlled signal generator and Picoscope are used to obtain the source (Ch A) and load (Ch B) voltages of this potential divider. The voltage waveforms are analyzed using correlation techniques in Matlab, to ensure that accurate impedance measurements are obtained. The correlation provides a significant immunity from interference on the SWER line. This same impedance analyzer was used to measure the transformer impedances. Due to the range of switched resistors used, our impedance bridge has a reduced accuracy for impedances above 1 MΩ. For lower impedances the accuracy is better than 0.2%.

For the transformer to be modeled, measurements were made for all the 5 available ports shown in fig. 2 over a wide range of frequencies. The impedance measurements were converted to magnitude and phase to obtain the error equations like (1) and (2) for all the 5 ports. The optimization to match the model to the measurements was then carried out.

III. Results

Fig. 4 to 8 show comparisons for the measured and modeled impedances. There is a very good agreement between the measurements and the model for all the measurements shown in fig. 5 to 8. For these measurements capacitive effects dominate. Fig. 4 shows that the impedance of the LV winding is more complex and as a result the agreement between the model and the measurements for the LV winding is not as good as that for the other ports.

Fig. 4 shows that between 10 Hz and 100 Hz the input impedance is inductive. This is due to the magnetic coupling. From 100 Hz to 5 kHz, the impedance is still governed by the magnetic coupling but the impedance becomes capacitive. From 5 kHz to 200 kHz the impedance is inductive and is governed by L1 in fig. 2. Above 200 kHz, the impedance is capacitive and is governed by C1 in fig. 2. The impedance seen at the LV terminals is very complex and would be very difficult to synthesize and match to the measurements using conventional mathematical techniques. However, the circuit optimization technique described in this paper yields an accurate solution without too much difficulty.

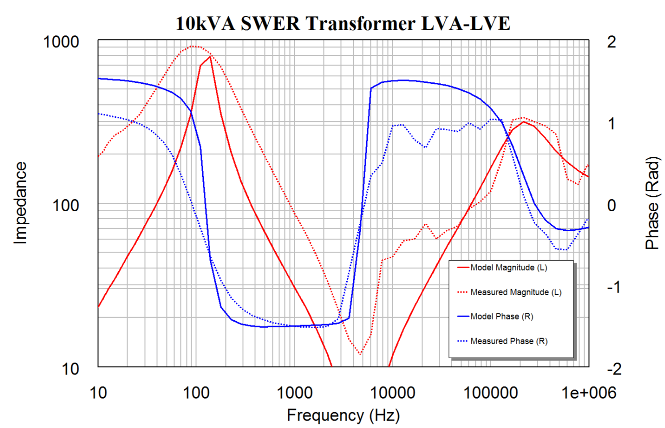

Fig. 4. LVa to LVe measured and modeled impedance.

Fig. 5 shows the impedance measured between the HVa and HVe terminals. The impedance corresponds to a 750 pF capacitance above 200 Hz. The dominant capacitances are the 490 pF capacitor C2 and the 580 pF capacitor C12 in fig. 2. Above 200 kHz, the losses are starting to increase as shown by the change in phase angle of the measured impedance.

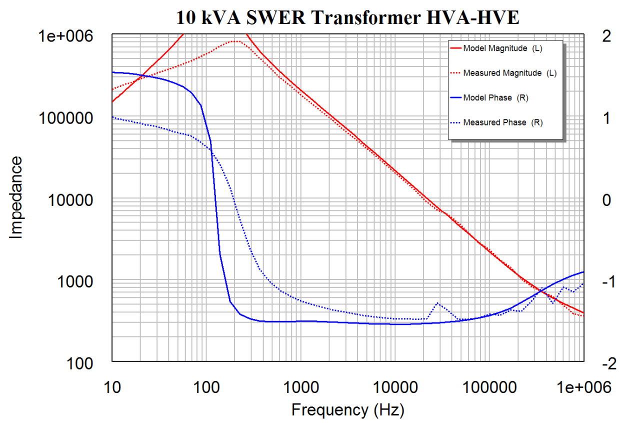

Fig. 5. HVa to HVe measured and modeled impedance.

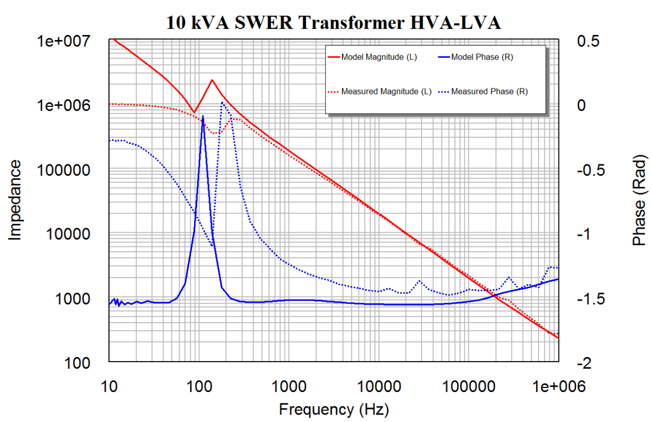

Fig. 6. HVa to LVa measured and modeled impedance.

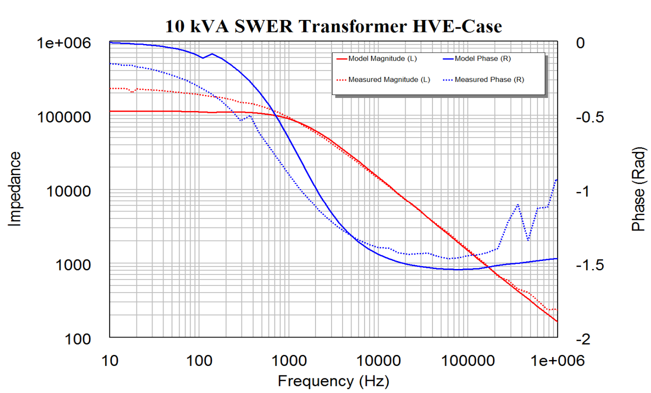

Fig. 7. HVE to Case measured and modeled Impedance

Fig. 6 shows the measured and modeled impedance between the HVa and LVa terminals. The impedance is capacitive above 200 Hz and represents the capacitive coupling between the HV and LV windings, with the transformer oil as the dielectric material between them. The impedance corresponds to an 800 pF capacitance and is made up of C12, with contributions of C2, C4, C5 and C1 in fig. 2. At high frequencies this impedance causes signals to leak from the LV side of the transformer to the HV side and vice versa. For conventional transformers this can cause high frequency switching noise from compact fluorescent lamps (CFL) and other power electronics to leak onto the HV network and interfere with existing PLC communications there.

Fig. 7 and 8 show the impedances between the transformer windings and the case. The impedance between HVe and the case corresponds to a 1.1 nF capacitance and is predominantly made up of the 870 pF capacitor C4 of fig. 2. The impedance between LVe and the case corresponds to a 1.04 nF capacitance and is predominantly made up of the 839 pF capacitor C5 of fig. 2.

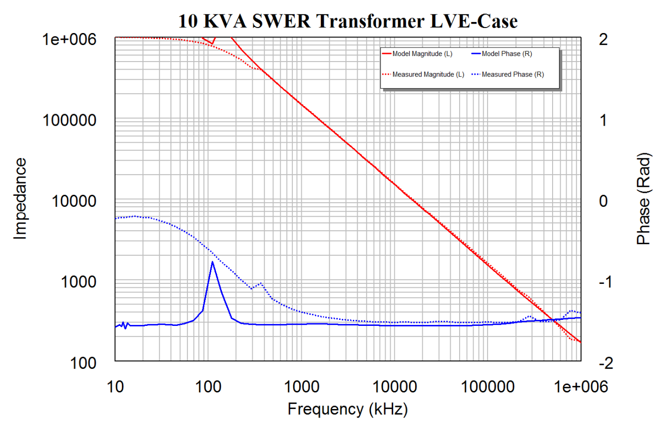

Fig. 8. LVE to Case measured and modeled impedance

It should be noted that since we are trying to develop a transformer model for PLC frequencies, the error equations like (1) and (2) are not evaluated below 500Hz. As a result the model is less accurate below 500Hz. If the model needs to be more accurate there, the complexity of the model will need to increase to model the magnetic circuit better.

IV. Coupling Networks

A. *LV Coupling*

The communication signals for the smart grid applications must be injected onto the typical 19.1 kV SWER line. In most cases the SWER line sending-end transformers have LV windings as well as the HV windings. The simplest way to inject the PLC signals onto the SWER line is to couple them onto the low voltage line and use the properties of the transformer to couple the signals onto the SWER line.

Fig. 9 shows the measured and modeled frequency response of the 10 kVA SWER transformer, when a 50 Ω source and load are used for the measurements. The frequency response obtained from the model and the measurements show a very good agreement and demonstrate that the transformer model can be used for system design. Fig. 9 shows that if the communication signals are coupled into the LVa terminals of transformers at both ends of the SWER line, approximately 80 dB insertion loss occurs due to the transformer coupling the signals on and off the SWER line. This is too big a loss for a practical system. It should be notes that above 1 MHz the losses become smaller, however the SWER line losses are much higher and those frequencies are outside the CENELEC-A frequency band set aside for power utilities. This type of coupling network is thus not practical.

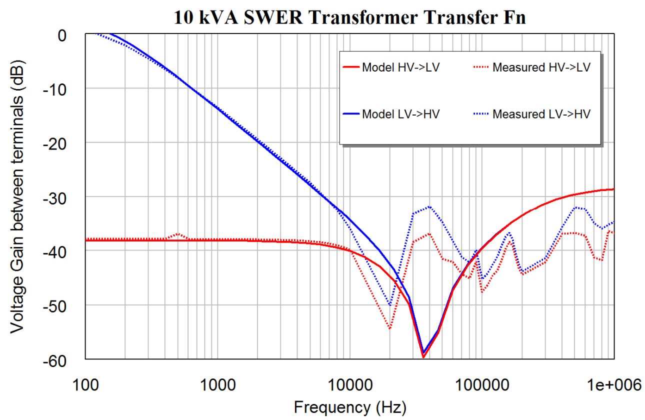

Fig. 9. Transformer Voltage Transfer Function.

B. *HV Capacitive Coupling*

The coupling network must provide a high attenuation to the mains frequencies, and it must pass the PLC frequencies. In addition, the network must provide an impedance transformation from the 330 Ω characteristic impedance at 75 kHz for the Steel Core Galvanized Zinc (SCGZ) SWER line or the corresponding 290 Ω for the Steel Core Aluminum Clad (SCAC) SWER line. Since our prototype system will be trialed on a SCGZ line, 330 Ω will be used.

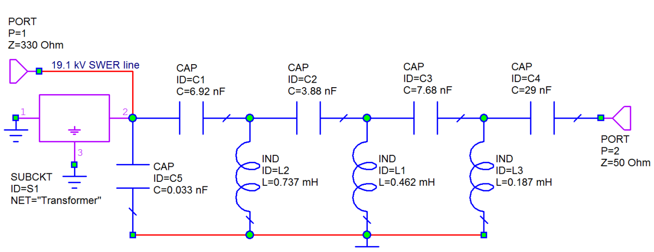

Fig. 10. Highpass Coupling Network and SWER Transformer.

Fig. 10 shows a typical coupling network, consisting of C1 to C4 and L1 to L3. C5 is a 33 pF capacitor representing the surge arrestor on the SWER line and "Subckt" S1 is the SWER line transformer model of fig. 1. The coupling network is designed using a series of high pass LC networks, based on the equations presented in Motorola application note AN267 [7, 8]. This network is then optimized both with and without the transformer being present to investigate the effect of the SWER line transformer. The final values with the transformer included are shown in fig. 10. The corresponding simulated frequency response is shown in fig. 11.

In practice this network cannot be realized economically as the 6.9 nF capacitor C1 needs to have a >20 kV AC rating and as a result is very expensive. Standard HV disk insulators have a 45 pF capacitance and are relatively cheap. For a >20 kV rating, three disks in series are required, so that a 15 pF HV capacitor can be obtained at low cost. Unfortunately the matching network Q values required to change the 6.9 nF C1 to 15 pF are too high and result in a very narrow bandwidth coupling network. This type of network is thus not practical.

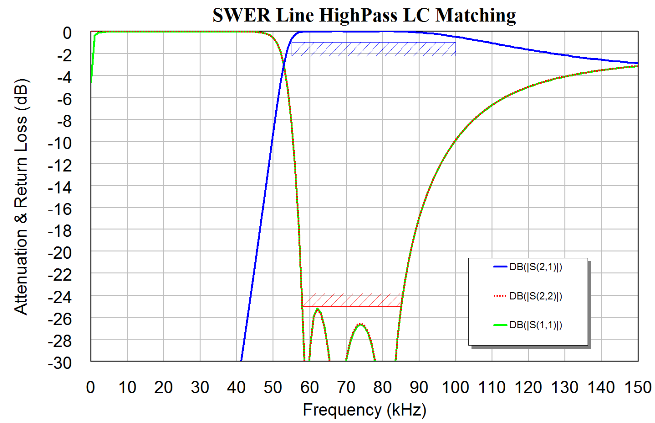

Fig. 11. Simulated performance of the network of fig. 10.

C. *HVe Coupling*

Since C2 of fig. 2 is 490 pF, the HV winding of the SWER line transformer can be used to replace C1 in the coupling network. The HV winding will thus be an integral part of the coupling network. Normally the HVe terminal is connected to the transformer case using a solid link. For this coupling network, the solid link is replaced with inductor L1 and the rest of the network of figure 12 is then connected across L1.

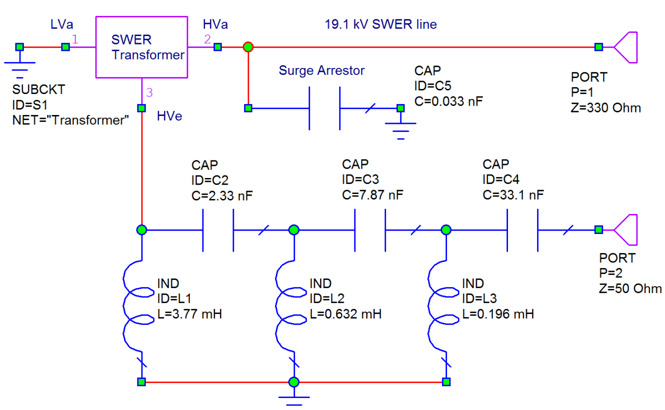

Fig. 12. HV Earth Link Coupling Network and SWER Transformer.

Fig. 12 shows the HV Earth link coupling network after optimization. The SWER line is connected to port 1 and the communication system modem to port 2. Fig 13 shows the corresponding simulated frequency response of the coupling network. The LVa terminal is grounded as this represents the worst case loading on the SWER line. However, opencircuiting the LV winding makes no noticeable difference to the transfer function shown in Fig. 13, as can be expected from a close inspection of the transformer model and from the 40 dB losses in fig. 9. The insertion loss of one coupler is 6.9 dB, making the total coupling loss 13.8 dB. Since the transformer is an integral part of the coupling network, different networks will need to be produced for different rating transformers.

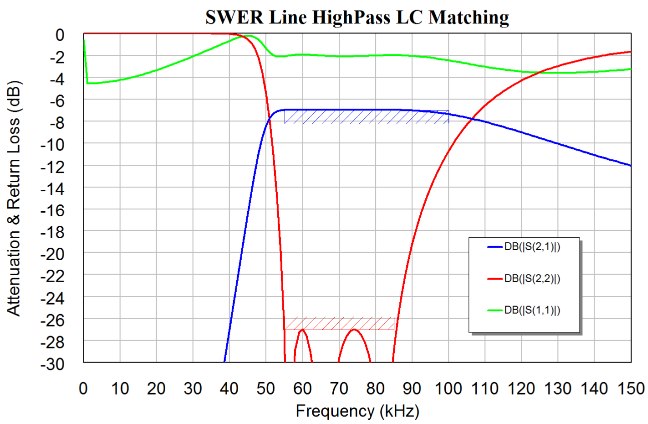

Fig. 13. Performance of the network of fig. 12.

Since the inductor L1 carries the full mains frequency SWER-line current, this inductor needs to be constructed such that it can handle this current without causing any saturation or heating. Since the HVe terminal would float to 19.1 kV if L1 were to become an open circuit, the physical integrity of L1 must be robust and observable. The voltage loss from the SWER line to the HVe terminal for the circuit of fig. 12 is 57 dB, so that for a 19.1 kV SWER line, a 38 mV 50 Hz signal occurs at the HVe terminal. At 50 Hz, a 396 dB voltage attenuation occurs between port 1 and port 2, so that no 50 Hz components can be detected at port 2. Reducing the circuit complexity from the 7th order circuit of fig. 12 to a 5th order one, reduces the -1 dB bandwidth of the coupler from 58.0 kHz in fig. 13 to 36.7 kHz for the 5th order circuit. The extra bandwidth allows more secure data communications and is thus worth the extra two components per coupling network.

The coupler hardware is being constructed and optimized to match the computer simulation.

V. CONCLUSIONS

This paper presents a novel technique for developing a model of a power transformer and using computer optimization, using circuit simulators to match the model to measurements of the transformer. Measurements of different SWER-line transformers of the same rating gave very similar impedance measurements, so that one model can be used for the same rating transformers. Different rating transformers only gave slightly different impedances, so that the same model with slightly different values can be used for those transformers. This technique can be applied to develop a high frequency model of any power transformer.

The model was used to develop a low cost coupling network to couple CENELEC-A frequencies onto SWER lines, to allow the implementation of smart grid control signals, the determination of the SWER line integrity and its losses and the measurement of power quality at the customer end of the SWER line. This coupling network could not have been developed without the detailed transformer model.

ACKNOWLEDGMENT

The author would like to thank ERGON ENERGY for their support in providing the funding for this research. The author would also like to thank the technical and academic staff at the School of Engineering and Physical Sciences at James Cook University, for their assistance and encouragement in this work. The author would specially like to thank Mr. Geoffrey Reid and Shani Boag for doing the many measurements of the transformers and Adrian Zatta for developing software for the semi automated impedance measurement system.

REFERENCES

[1] Kikkert, C. J. and Reid G,. "Radiation and Attenuation of Communications Signals on Power Lines" 7th International Conference on Communications and Signal Processing, ICICS 2009, 8-10 December 2009, Macau

[2] Joan, D. Munteanu, I. Models for capacitive effects in iron core transformers. 2000: IEEE Transactions on Magnetics Volume: 36, Issue: 4, Part 1. pp 990-994

[3] Degeneff, R.C., Gutierrez, M.R., Vakilian, M. Nonlinear, lumped parameter transformer model reduction technique. 1995: IEEE Transactions on Power Delivery. Volume: 10, Issue: 2. pp 862-868

[4] Biernacki, J., Czarkowski, D. High frequency transformer modeling. 2001: The 2001 IEEE International Symposium on Circuits and Systems. ISCAS 2001. Volume: 3. pp676-679 vol 2.

[5] Gorman, M.J., Grainger, J.J. Transformer modeling for distribution system studies. 1. Linear modeling basics. 1992: IEEE Transactions on Power Delivery. Volume: 7, Issue: 2. pp 567-574

[6] Gustavsen, B. Wideband modeling of power transformers. 2004: IEEE Transactions on Power Delivery. Volume: 19, Issue: 3 pp 414-422.

[7] Davis F. Matching Network Designs with Computer Solutions, Motorola Application note AN267/D, Motorola 1993, available from: http://www.freescale.com/files/rf_if/doc/app_note/AN267.pdf.

[8] Kikkert C. J. "RF Electronics Lecture notes, Chapter 9: Impedance Matching of Power Amplifiers", from "RF and Microwave Electronics Design Course as used by James Cook University. Available from: http://web.awrcorp.com/Usa/Contact/University-Program/