Power Line Carrier Communications System Modeling

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Abstract — This paper presents the results of the development and application of a power line communication components library, including single and double-frequency line traps, line tuning units, CCVTs, transmitters, receivers, balanced and skewed hybrids, and signal level probes. The library is developed for ATP-EMTP using ATPDraw. Benchmarking of laboratory measured characteristic versus model behavior has been carried out for the particular components.

System level simulation of a power line carrier system is performed to demonstrate the modeling capabilities. This approach is a marked advancement over traditional steady-state model analysis methods.

Keywords: power system communication, power system modeling, attenuation, ATP-EMTP.

I. Introduction

Even in today's world of high speed internet and fiber optics, traditional Power Line Carrier (PLC) is still widely used to provide real-time communications for protection of high voltage transmission lines. PLC is often the most economical and reliable high-speed dedicated channel available for protective relaying.

A power line carrier system includes three basic elements: a transmission line, presenting a channel for the transmission of carrier energy; tuning, blocking, and coupling equipment, providing a means of connection to the high-voltage transmission line; and transmitters, receivers and relays. The simplified functional diagram of a power line carrier system is shown in Fig. 1 [4].

This library of basic components for modeling of PLC communications systems is implemented in ATP-EMTP. Earlier work [3] is extended here.

Functionality for each library component is discussed, and the benchmarking of simulation results versus laboratory measurements is presented. ATP provides a way for analyzing the PLC behavior both in time- and frequency-domain. This makes it possible to evaluate carrier attenuation as well as perform frequency scans. One can thus evaluate and choose best carrier frequencies, and compare performance of various coupling configurations. A practical example case of applying the developed library to a 115-kV transmission system is presented.

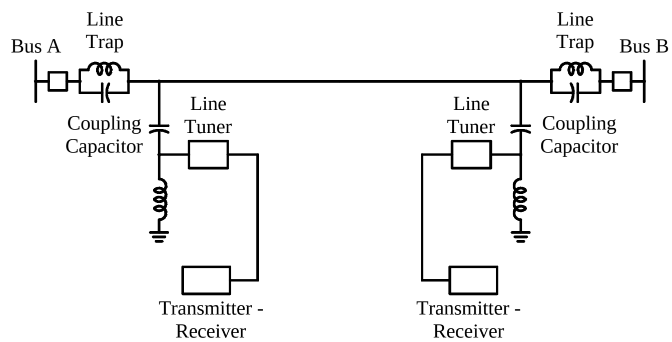

Fig. 1. Power line carrier communication system.

Frequency-dependent transmission line models are used to represent transmission line sections for simulation purposes.

It is anticipated that these modeling tools will allow engineers to evaluate proposed designs and trouble-shoot problematic installations, with the aim of choosing optimum frequencies and modes of coupling, maximizing the performance and reliability of PLC systems, and thus improving power system security.

II. Library of Components

The power line carrier component library at its current stage of development includes the following components: line traps, line tuning units, coupling capacitors, balanced resistive and reactance hybrids, skewed hybrids, carrier transmitter, and dBm probes.

A. Line Traps

Line traps provide blocking of the carrier signal, preventing it from continuing into other transmission line sections.

Single and two-frequency line traps are parallel L-C circuits with parameters of variable inductances and capacitances selected so as to resonate at a specific frequency (or at two frequencies) thus blocking the carrier frequency (Fig. 2).

Line traps are available in various inductance ratings and continuous power-frequency current ranges [4].

ATP models for both single- and two-frequency line traps have been developed, and the library components for line traps are shown in Fig. 3.

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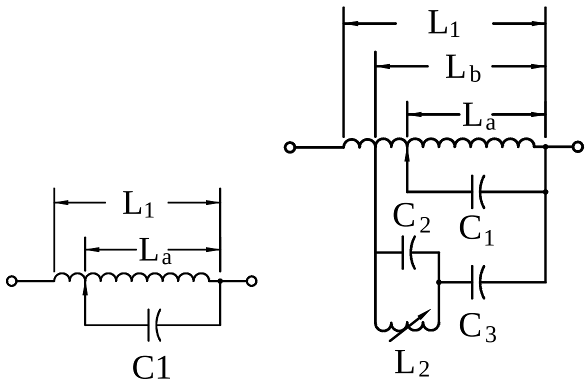
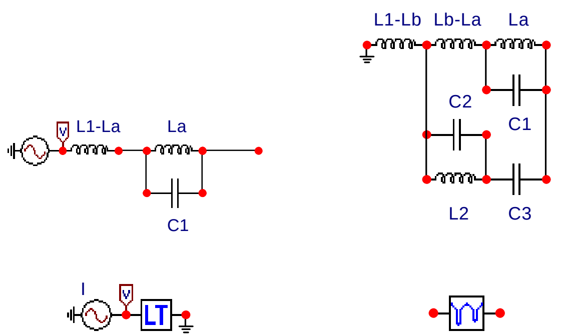


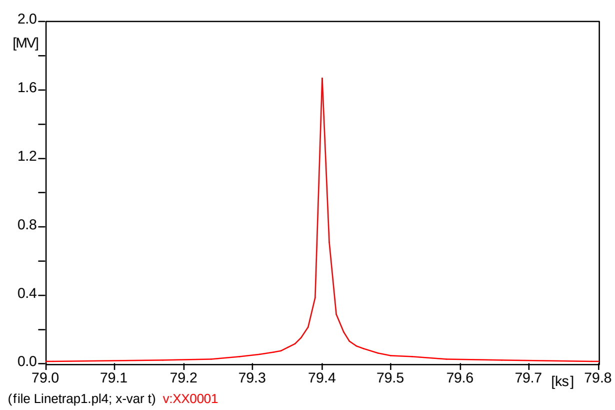
a) Single-frequency b) Two-frequency

Fig. 2. Equivalent circuit diagrams of line traps

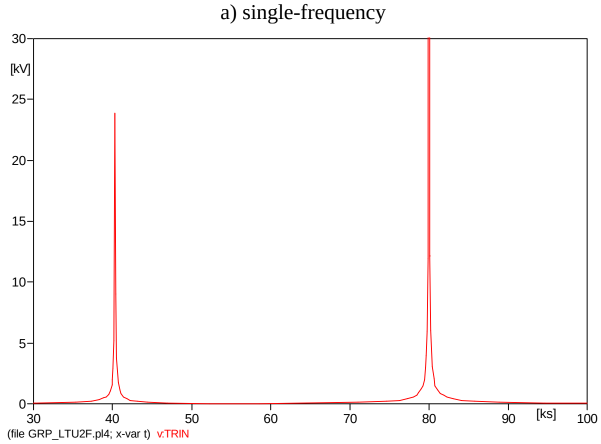


a) Single-frequency b) Two-frequency

Fig. 3. ATP line trap models and resulting ATPDraw library symbols.



a) single-frequency



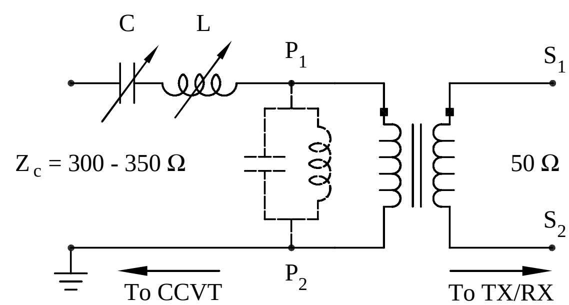
b) two-frequency

Fig. 4. Frequency Scan of the line trap.

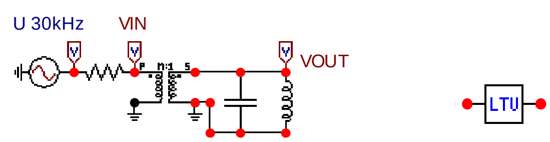
ATP's Frequency Scan can be used to verify the attenuation and Q-factor of the line traps, as shown in Fig. 4.

B. Line Tuning Units

Line tuning units (LTUs) or "line tuners" are used to tune to the carrier frequency and provide impedance matching between the power line and the transmitter/receiver. The LTU includes an impedance-matching transformer, a series-resonant L-C circuit tuned to the carrier frequency, and also a protective device [4]. A functional diagram and the ATPDraw library component for an LTU are shown in Fig. 5 with an optional L-C circuit (trap unit), which is required for wide-band LTUs shown as dashed lines.



a) Equivalent circuit



b) ATP model and ATPDraw library symbol

Fig. 5. Line tuning unit.

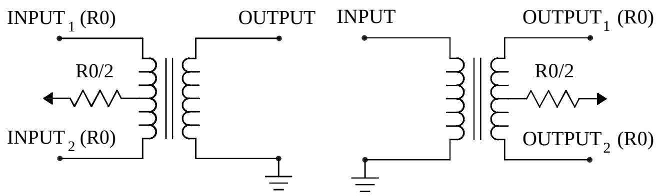
The ATP Line/Cable Constants routine provides a way to obtain the characteristic impedance of the transmission lines at the desired power line carrier frequency. This information then can be used to set the parameters of an LTU in order to provide impedance matching.

C. Hybrids

Auxiliary coupling devices can be defined as any component of a PLC coupling scheme used to mix or separate transmit/receive frequencies on the 50 Ω side of the LTU [4]. Hybrids and filters are passive auxiliary coupling devices, as opposed to active devices which combine PLC functions using unidirectional amplifiers. The hybrids can work in both directions (bilateral), and therefore can be applied for cases of two inputs and a single output or one input and two outputs, as shown in Fig. 6 for the resistive hybrid.

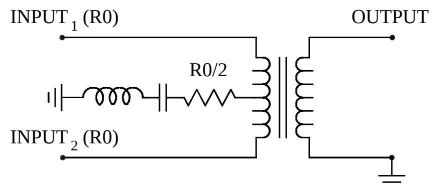
Fig. 7 shows the circuit diagrams for reactance and skewed hybrids.

ATP models for the resistive balanced hybrid, the reactance hybrid and the skewed hybrid (a modification of the Wheatstone bridge circuit where unequal amounts of power are divided between a source and a sink) have been created (Fig. 8).

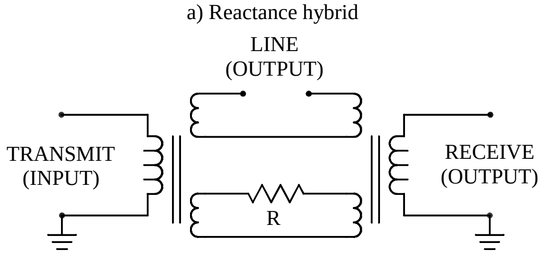


a) One input and two outputs b) One output and two inputs

Fig. 6. Equivalent diagram of balanced restive hybrid.

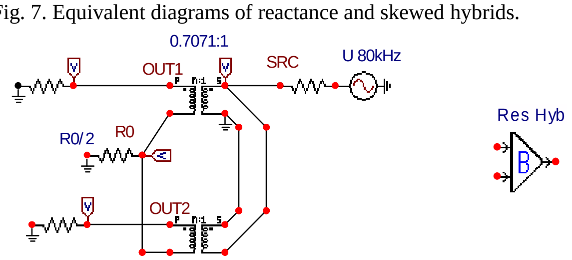


a) Reactance hybrid

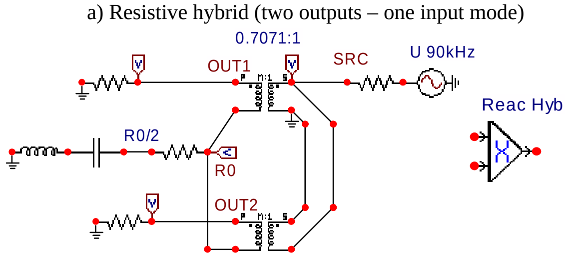


b) Skewed hybrid

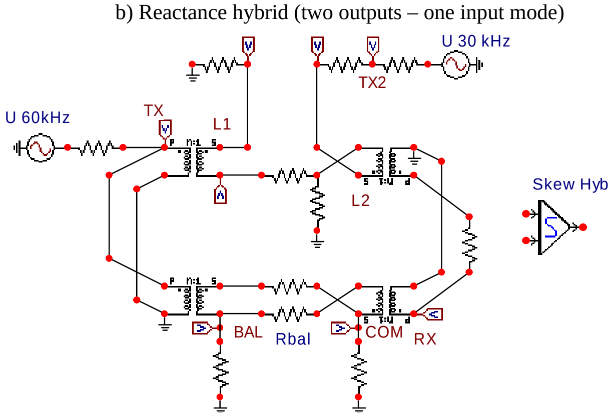
Fig. 7. Equivalent diagrams of reactance and skewed hybrids.



a) Resistive hybrid (two outputs – one input mode)



b) Reactance hybrid (two outputs – one input mode)

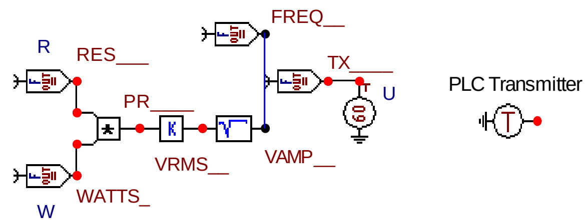


c) Skewed hybrid

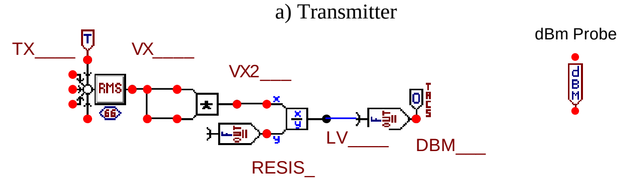
Fig. 8. ATP models of the hybrids and resulting ATPDraw library symbols.

D. Miscellaneous Components

Additional library components include a PLC transmitter, which calculates the 50-Ohm output voltage amplitude based on the specified power (typically 10 W for trip and 1 W for guard), PLC frequency and impedance, and the dBm probe, which provides direct measurement of signal power in decibels referred to 1 mW. These components are implemented in ATP using TACS and the Data Base Module features. The ATPDraw library components are shown in Fig. 9.



a) Transmitter



b) dBm probe

Fig. 9. ATP Draw models and resulting ATPDraw library symbols for the miscellaneous components.

III. Laboratory Measurements and Benchmarking

Laboratory measurements and benchmarking of the resistive, reactance and skewed hybrids, and of the line tuning unit were performed to confirm the functionality of these models and quantify their frequency response.

Function generators capable of up to 15 MHz were used as the high frequency sources for laboratory measurement purposes. A digital oscilloscope was used to capture the input and output waveforms from the equipment being tested. The performance of the PLC equipment has been evaluated in the range of 30-450 kHz, and the percent error between the output voltages of the ATP model and the laboratory measurements was calculated.

Benchmarking of the balanced resistive hybrid [5] is shown here as an example.

To verify the turns ratio, the source is connected to the output port, and voltages at the two input ports are measured, as shown in Fig. 10. When the source is applied, the signal is split into two signals of equal amplitude and opposite phase thus giving the voltage ratio from which the turns ratio can be verified.

Fig. 11 shows the waveforms from laboratory measurements and ATP simulation at 30 kHz, confirming that the voltages of the Source, Input1 and Input2 are essentially identical. It can be observed that the V_{output} is in phase with V_{input2} and out of phase with V_{Input1}. The percent error between the measured and simulated signals in this case does not exceed 1% in the range of 30-450 kHz.

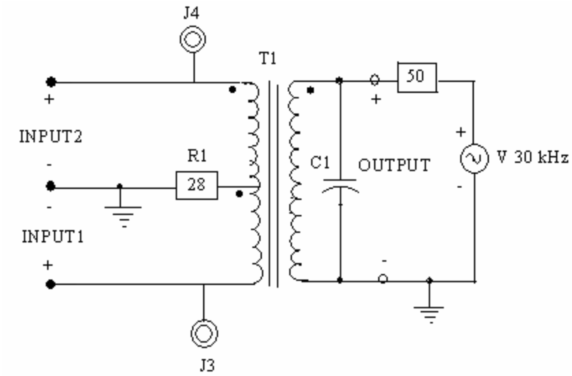


Fig. 10. Lab Setup.Verifying Turns Ratio.

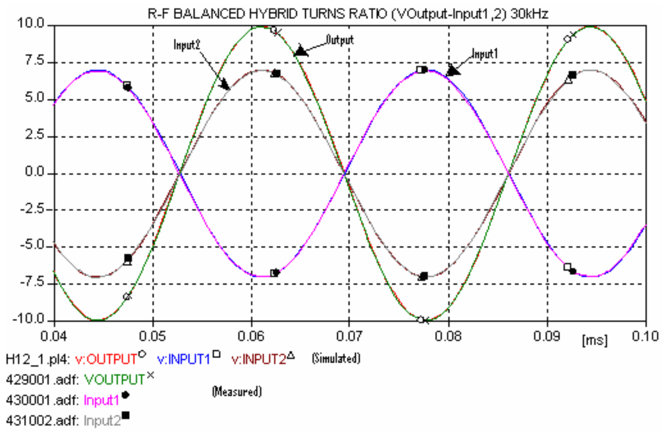


Fig 11. Waveforms of measured and simulated terminal source voltages (Output along with Input 1 and Input 2).

The two-frequency mode of operation has also been tested. To measure the output waveform, which is in this case a combination of the two input frequencies. The two sources are applied: one of 100 kHz at Input 1 and the other of 200 kHz at Input 2. The Output is terminated with 50 Ohms impedance as shown in Fig. 12.

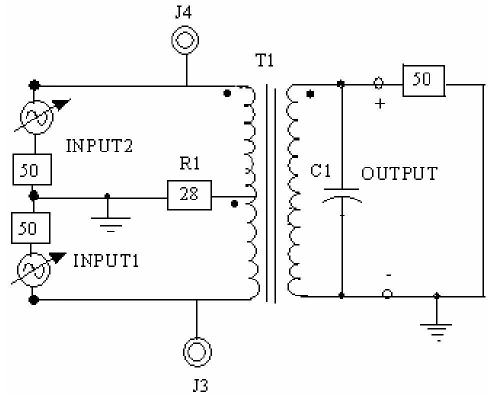


Fig. 12. Lab Setup. Two Input Frequencies.

Fig. 13 shows the waveforms of laboratory measured and ATP simulated input and output voltages of the R-F balanced resistive hybrid. It can be observed that that the Output is a combination of Input 2 and Input 1.

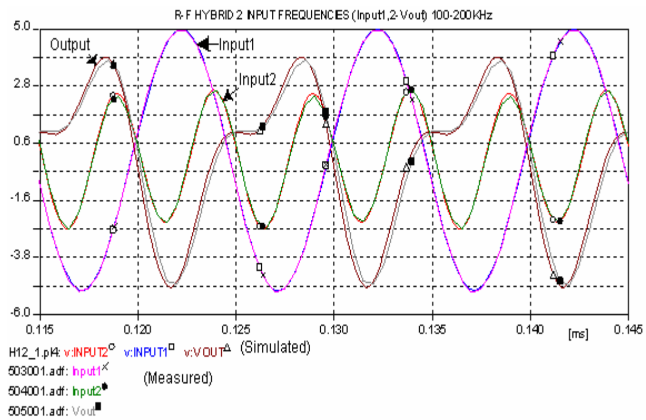


Fig. 13. Waveforms of Measured and Simulated Terminal Source Voltages (Input 1, Input 2) along with Output.

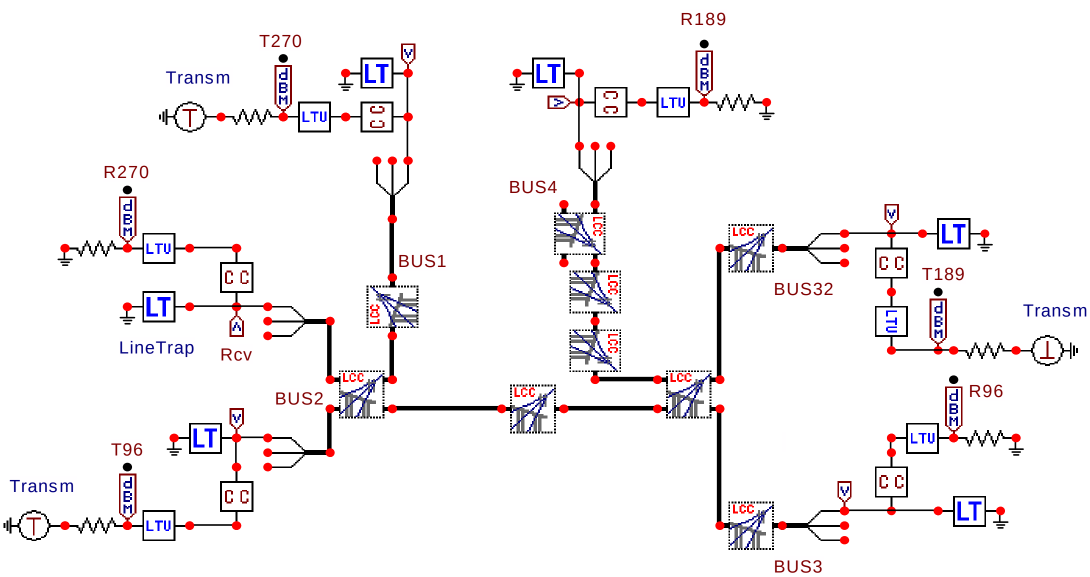


Fig. 14. ATPDraw model of the system.

Based on peak values of the output waveforms, the percent error between measured and simulated results for this case is found to be 2.9 %. This resistive hybrid was also tested for another case involving 30 and 400 kHz with an error of 5.7%.

The reactance hybrid [5] has similar characteristics, and so was tested in a similar way. The skewed hybrid was also tested for turns ratio, with the model providing a good match.

The Line Tuning Unit (LTU) [6] was not tested in its entirety, but a shunt L-C trap unit (which can optionally be connected between terminals P_1 and P_2 of Fig. 5a) was tested and compared against an ideal L-C circuit in ATP. Errors of as high as 20% are possible at 450 kHz.

In general, the performance of the ATP library components tends to decrease with an increase of frequency and can be noticeable above 200 kHz. This is due to fact that the models at this time utilize ideal transformers and do not yet include frequency-dependency beyond what is predicted by the linear L-C elements. Laboratory measurements and model benchmarking is continuing, with results being used to improve the accuracy of the library components in the higher frequency ranges.

IV. Library Application

A 115-kV test system is configured as shown in Fig. 14. Power line carrier equipment is installed at both ends of each transmission line. Frequency-dependent JMarti line models have been created for the three lines 1 – 2, 2 – 3, and 3 – 4. This part of the grid has a number of single-circuit and double-circuit line sections (each section is modeled as a separate Line Constant object in ATPDraw). With different PLC frequencies being used on each line, this is a good study example. Effectiveness of tuning and blocking filters, selection of frequencies appropriate to line characteristics, and coupling of carrier frequencies between double circuit lines can be simulated. Results can be used to verify or improve performance.

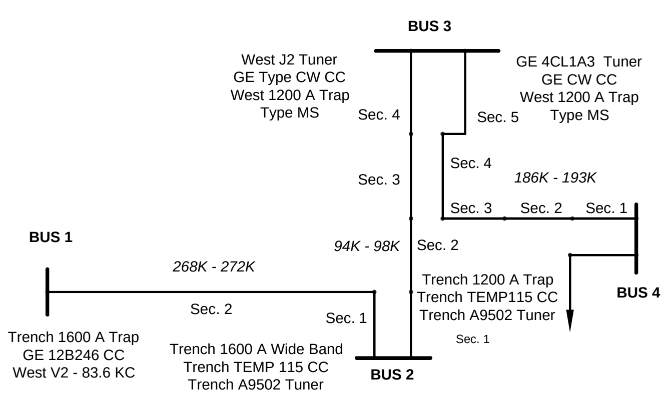


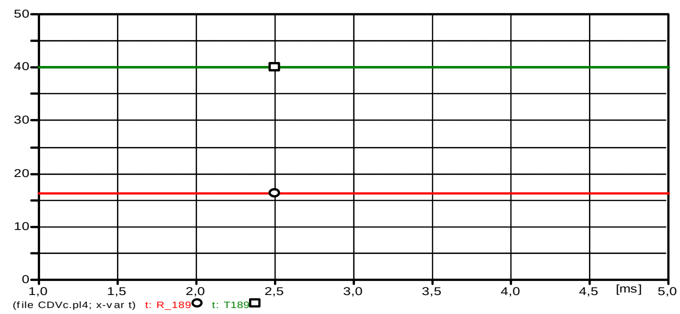
Fig. 15. Configuration of the system.

Transmission lines, involved in the study are as follows:

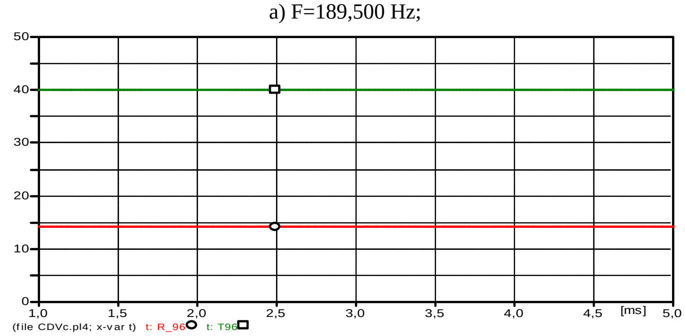
- 1 – 2: Has a single-circuit section and a double circuit section. Feasible PLC frequency range according to the equipment spec is 168-272 kHz, with 270 kHz selected for the modeling purposes.
- 2 – 3: Consists of two double-circuit and two single-circuit sections. Feasible PLC frequency range according to the equipment spec is 94-98 kHz with 96 kHz selected for the modeling purposes.
- 3 – 4: Has two double-circuit and three single-circuit sections. Feasible PLC frequency range according to the equipment spec is 186-193 kHz with 189.5 kHz selected for the modeling purposes.

The ATPDraw model of the system including PLC equipment is shown in Fig. 15.

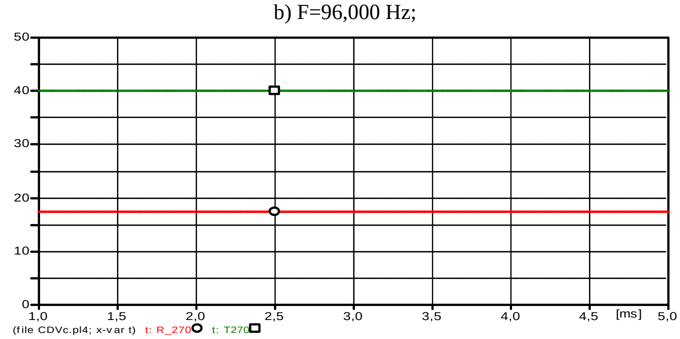
Fig. 16 gives the transmit and receive signal levels in dBm for each line. The results show that the performance of the PLC communication system in this case satisfies the recommended 15 dB operating margin 1.25 V at 50 Ω [4] in all cases, except for the 96 kHz frequency. It can be recommended that the carrier frequency for this line should be re-selected to improve the PLC system performance.



a) F=189,500 Hz;



b) F=96,000 Hz;



c) F=270,000 Hz;

Fig. 16. dBm levels at transmitting and receiving ends

It is also of interest to consider the distortion effects of other carrier frequencies which are present due to coupling with double circuit or adjacent lines. Fig. 17 illustrates the performance of line 2-3 with and without the presence of carrier frequencies on the other lines. In this example there is a drop of 1 dBm in the received signal. Further analysis could be done to determine if this could cause any performance problems.

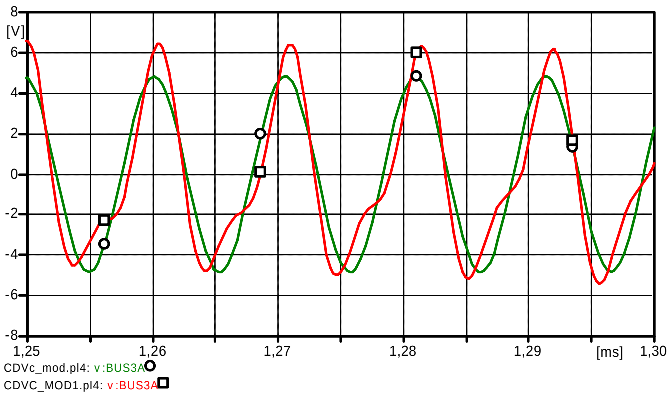


Fig. 17. Comparison of received carrier signal on line 2-3 at Bus 3, with and without distortions caused by carrier frequencies of adjacent lines.

Frequency scans can also be simulated to determine the most suitable frequencies that best match frequency-dependent behavior of the power transmission lines. More importantly, frequencies that experience high attenuation or cause interference can be identified and avoided. ATP's basic Frequency Scan capabilities can be used to do this, as illustrated in Fig. 4.

V. Conclusions

The library of PLC components developed and the modeling approach outlined here make it possible to predict performance of complex systems with many co-existing carrier frequencies. Simulation in the time domain using the various EMTP programs makes it possible to include the effects of frequency-dependent transmission lines, perform frequency scans, and observe harmonic distortions. The presently available components are robust from 30 kHz up to 200-300 kHz.

VI. Future Work

Future work is focused on continued benchmarking and improved accuracy of the library of components in higher frequency ranges. It is recommended that simulated results be compared against actual field measurements. It could be useful to develop library of components that facilitate frequency scans, interpret results, and make recommendations on selection of carrier frequency.

VII. References

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VIII. Biographies

Bruce A. Mork (M'82) was born in Bismarck, ND, on June 4, 1957. He received the BSME, MSEE, and Ph.D. (Electrical Engineering) from North Dakota State University in 1979, 1981 and 1992 respectively.

From 1982 through 1986 he worked as design engineer for Burns and McDonnell Engineering in Kansas City, MO, in the areas of substation design, protective relaying, and communications. He has spent 3 years in Norway: 1989-90 as research engineer for the Norwegian State Power Board in Oslo; 1990-91 as visiting researcher at the Norwegian Institute of Technology in Trondheim; 2001-02 as visiting Senior Scientist at SINTEF Energy Research, Trondheim. He joined the faculty of Michigan Technological University in 1992, where he is now Associate Professor of Electrical Engineering, and Director of the Power & Energy Research Center.

Dr. Mork is a member of IEEE, ASEE, NSPE, and Sigma Xi. He is a registered Professional Engineer in the states of Missouri and North Dakota.

Dmitry Ishchenko was born in Krasnodar, Russia. He received his M.S. and Ph.D. degrees in Electrical Engineering from Kuban State Technological University, Russia in 1997 and 2002 respectively. In September 2000 he was awarded with the Norwegian Government Research Scholarship and worked as a visiting researcher at the Norwegian Institute of Science and Technology (Norway). His experience includes 5 years as Power Systems Engineer at the Southern Division of the Unified Energy System of Russia.

In February 2003 he joined the Electrical and Computer Engineering Department of Michigan Technological University as a postdoctoral researcher. His research interests include computer modeling of power systems, power electronics, and power system protection.

Dr. Ishchenko is a member of the IEEE Power Engineering Society.

Xingkang Wang received his B.S and M.S degrees from Sichuan University (China) and the University of Toledo in 1997 and 2003 respectively. He had worked as a system operation engineer for Sichuan Electric Power Corp for 4 years. Currently, he is PhD Candidate in the Department of Electrical Engineering, Michigan Tech University. His research interests include power system modeling and control.

Ajitha Yerrabelli received a Bachelors in Electrical and Electronics Engineering from Osmania University, Hyderabad, India in May 2003 and an MSEE from Michigan Technological University, Houghton, MI in December, 2004. Her experience includes an internship with Patrick Engineering Inc., where she worked on SCADA redirection project.

Currently she is with Patrick Engineering Inc., working as a designer.

Richard P. Quest received his BSEE from University of Minnesota in 1979. He has worked with transmission and protective relaying for Minnesota Power, HDR Techserve, Consolidated Services, and since 1986 at Northern States Power (now Xcel Energy) where he is presently Principal Engineer in Operations.

Charles P. Kinne received his BSEE from University of Minnesota IT in 1981. He has been with NSP/Xcel Energy since Sept. 1979. Presently he is working as a Senior Engineer in the Substation Maintenance Engineering group.