A Look into Steady State and Transient Performance of Power Lines Integrating Single Wire Earth Return Circuits

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Abstract - **In order to get a descriptive picture of the effect of ground properties on a distribution line, a comparison between a two-phase line with neutral return and a Single Wire Earth Return (SWER) line is carried out. Both, steady state and transient performance are assessed. The impact of relevant parameters such as line length, grounding resistance at the customer site and soil resistivity along the SWER line is integrated in the analysis. Results reveal important aspects that can assist in deciding acceptable operating limits of the SWER system, particularly regarding voltage drop, increased losses due to the normally small size of single phase conductors, faults, etc. All simulations were conducted using PSCAD V4.**

***Index Terms*—SWER, , earth resistivity, isolation transformer, steady state, transient, PSCAD, power quality**

I. Introduction

SWER systems are used in some parts of the world where electricity has to be delivered to extended areas in rural communities with low population densities, notably in Brazil, Australia, New Zealand, Africa, India, Latin America and Canada [1,2]. Loads are typically light but the extension of the single wire circuits can often reach 200, 300 and even 400 km. Also, due to the small size of the conductors voltage drop and increased losses are important issues for utilities. Frequently, lines span across soils of varying resistivity and getting low grounding resistance values at customer sites often require of improved grounding methods.

Nevertheless, the cost of the SWER system still represents a significant reduction over the three-phase system and this may be the most appealing aspect to some utilities. A practical issue is the voltage regulation problem since long lines can develop considerable voltage drops. SWER systems are special in that the return path of the zero sequence current is through the earth. There have always been arguments on whether the resistivity of the ground, which may vary locally and even be dependent on weather/season , can be accurately reproduced through analytical treatment.

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This has triggered numerous studies to describe the earth return path impedance, among which the leading works by Carson [3] and Pollaczek [4] can be mentioned. PSCAD solves the ground impedance integral (either Carson or Pollaczek) through analytical approximation or by direct numerical integration. The latter option was chosen in the simulations presented in this work.

Given the limited knowledge on the impact of the earth return impedance in voltage and current under steady state and transient conditions in the SWER system, this paper makes a comparative assessment of the performance of the SWER system alongside a two-phase system, looking at the steady state and transient conditions.

II. COMPARATIVE STEADY STATE PERFORMANCE

Figure 1 shows a partial diagram of the PSCAD circuit used for the study which comprises a couple of lines, one being a two-phase system and the other a single phase line SWER. The two lines have similar length and grounding resistance. The comparison included the simultaneous testing of similar pairs of lines encompassing different soil resisitivity and grounding resistance values. Soil resistivity was varied assuming values of 100, 1000 and 4000 ohms-m to consider lands from agricultural to sandy/clay to gravel kind of soil. Grounding resistance values assumed were 10 and 20 ohms, which are typical values for distribution transformer grounding in this type of installations [1]. A concentrated load including 2.5 MW, 1 MVAR inductive and 0.35 MVAR capacitive elements was assumed for every line so as to replicate a light loading condition, since the substation transformer assumed was 10 MVA. Under this loading scenario, the power factor at the substation yields around 0.98-0.99.

The two-phase line extends to reach the far end to supply a customer served from a 22/0.250 kV distribution transformer while the SWER line taps from the three phase feeder through a 150 kVA isolation transformer and from there it extends to reach the customer connected at the far end served from a 12.7/0.250 kV distribution transformer. Both transformers are assumed loaded to rated power and grounded through a 2 ohm resistor. A #4 ACSR conductor as typical in New Zealand for these systems [1] was assumed for the two lines.

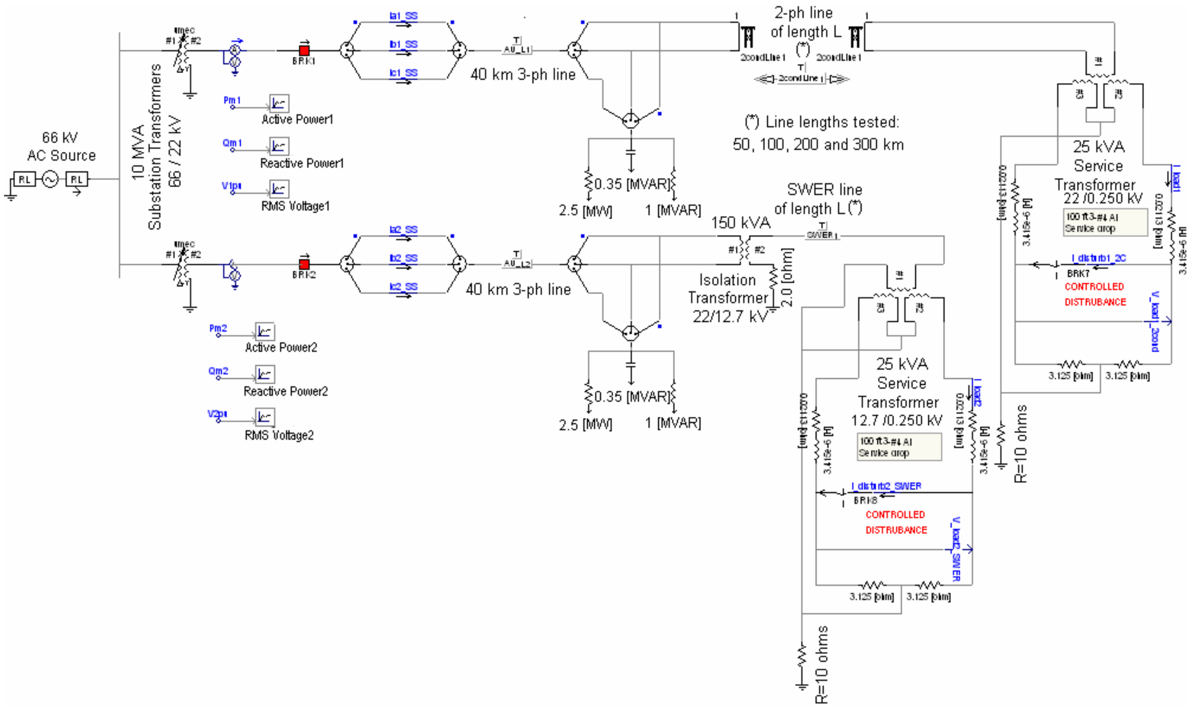


Figure 1. Circuit diagram of the tested scenario for specific line lengths and soil resistivities

Tables 1-3 show the active, reactive and apparent power obtained in the simulations. The cases listed in the first column of these tables are as follows:

L50_R10: Length line 50 km, grounding resistance of the customer service transformer 10 Ω
L50_R20: Length line 50 km, grounding resistance of the customer service transformer 20 Ω
L100_R10: Length line 100 km, grounding resistance of the customer service transformer 10 Ω
L100_R20: Length line 100 km, grounding resistance of the customer service transformer 20 Ω
L200_R10: Length line 200 km, grounding resistance of the customer service transformer 10 Ω
L200_R20: Length line 200 km, grounding resistance of the customer service transformer 20 Ω
L300_R10: Length line 300 km, grounding resistance of the customer service transformer 10 Ω
L300_R20: Length line 300 km, grounding resistance of the customer service transformer 20 Ω

The rest of the columns list the mentioned parameters for the 2-conductor (2C) and for the single conductor (SWER) lines. Results in table 1-3 and figures 2-4 reveal that although increased values of reactive power are associated with the SWER system, particularly at the longer line lengths considered, the total or apparent power for the assumed loading condition yields smaller values for the SWER system.

Table 4 and figure 5 show that increased apparent power, mainly from a reactive power raise, in excess of 5% relative to the base case (L50_R10) will occur when line length is 200 km or longer. Also, the biggest difference between the two-conductor and the SWER lines is found for ρ=1000 Ω-m.

Power factor is somewhat lower for the SWER system as illustrated in figure 6, but still varying within a narrow band.

Table 1
Feeder MW

Soil Resistivity (Ω-m):	100		1000		4000	
Case:	2C	SWER	2C	SWER	2C	SWER
L50_R10	2.71	2.68	2.7	2.7	2.7	2.69
L50_R20	2.7	2.68	2.7	2.68	2.71	2.7
L100_R10	2.76	2.71	2.75	2.71	2.76	2.71
L100_R20	2.76	2.71	2.76	2.71	2.76	2.71
L200_R10	2.87	2.75	2.86	2.76	2.84	2.76
L200_R20	2.87	2.76	2.87	2.76	2.88	2.77
L300_R10	2.99	2.81	2.99	2.82	2.99	2.81
L300_R20	2.98	2.82	2.99	2.81	2.99	2.82

Table 2
Feeder MVAR

Soil Resistivity (Ω-m)	100		1000		4000	
Case	2C	SWER	2C	SWER	2C	SWER
L50_R10	0.55	0.57	0.54	0.57	0.54	0.57
L50_R20	0.54	0.57	0.54	0.57	0.55	0.57
L100_R10	0.50	0.56	0.51	0.55	0.50	0.56
L100_R20	0.50	0.56	0.49	0.56	0.50	0.56
L200_R10	0.44	0.55	0.45	0.52	0.44	0.53
L200_R20	0.43	0.54	0.44	0.55	0.42	0.54
L300_R10	0.39	0.54	0.37	0.52	0.39	0.51
L300_R20	0.37	0.53	0.39	0.54	0.37	0.52

Table 3 Feeder MVA						
Soil Resistivity (Ω-m):	100		1000		4000	
Case:	2C	SWER	2C	SWER	2C	SWER
L50_R10	2.77	2.74	2.75	2.76	2.75	2.75
L50_R20	2.75	2.74	2.75	2.74	2.77	2.76
L100_R10	2.80	2.77	2.80	2.77	2.80	2.77
L100_R20	2.80	2.77	2.80	2.77	2.80	2.77
L200_R10	2.90	2.80	2.90	2.81	2.87	2.81
L200_R20	2.90	2.81	2.90	2.81	2.91	2.82
L300_R10	3.02	2.86	3.01	2.87	3.02	2.86
L300_R20	3.00	2.87	3.02	2.86	3.01	2.87

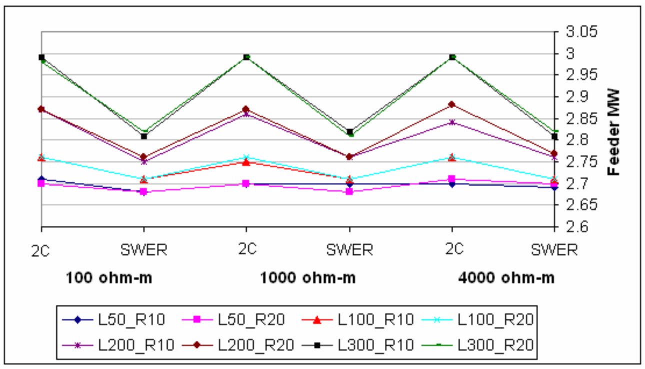


Figure 2. Feeder MW calculated values

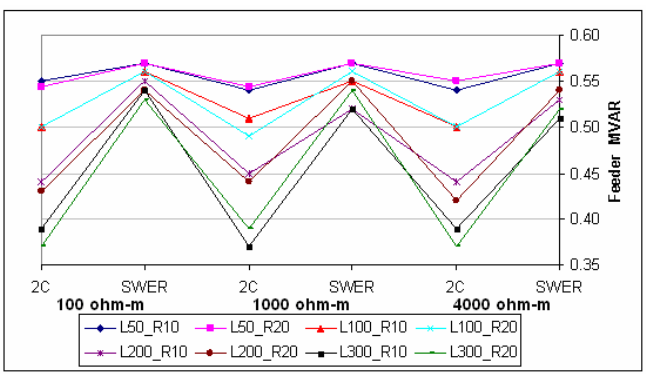


Figure 3. Feeder MVAR calculated values

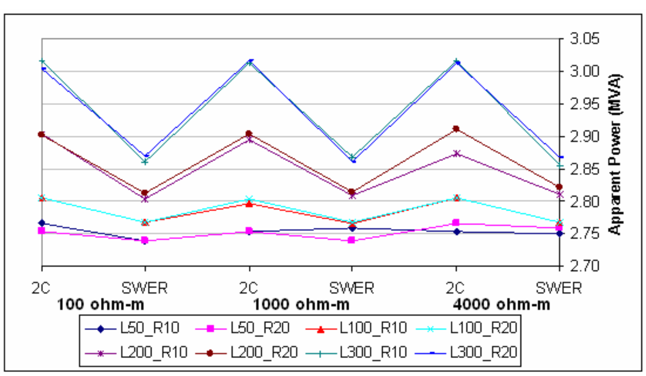


Figure 4. Feeder MVA calculated values

Table 4 Feeder increased MVA in % of base case (L50-R10)						
Soil Resistivity (Ω-m):	100		1000		4000	
Case:	2C	SWER	2C	SWER	2C	SWER
L50-R10	0.00	0.00	0.00	0.00	0.00	0.00
L50_R20	-0.39	0.00	0.03	-0.71	0.43	0.36
L100_R10	1.43	1.00	1.58	0.21	1.87	0.64
L100_R20	1.43	1.00	1.80	0.28	1.87	0.64
L200_R10	5.00	2.35	5.15	1.78	4.37	2.21
L200_R20	5.00	2.35	5.15	1.78	4.37	2.21
L300_R10	9.04	4.43	9.42	3.91	9.51	3.86
L300_R20	8.59	4.72	9.51	3.69	9.42	4.28

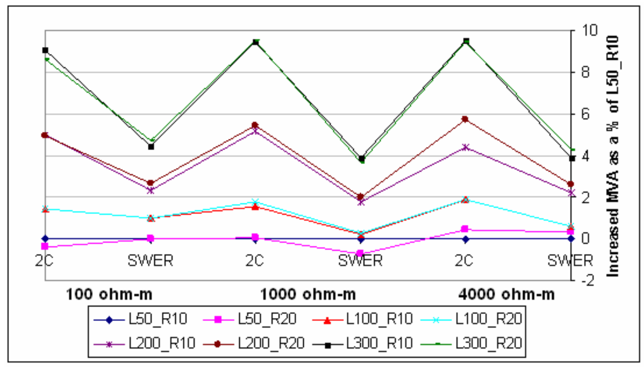


Figure 5. Increase of MVA relative to the base case

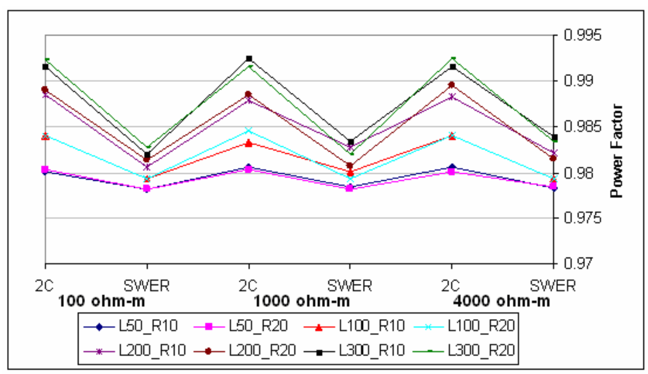


Figure 6. Calculated Power factor for the several cases

Regarding voltage at the far end, table 5 and figure 7 show that a voltage decrease to around 94% and lower relative to nominal will occur for line lengths 300 km and above. This is somewhat more pronounced for the SWER system. This violates usual recommended industry values, which advocate for voltage variations within 6% of nominal.

Utilities using very long SWER lines usually apply and will continue to implement appropriate voltage regulation measures to maintain the far end voltage within recommended levels.

Table 5 Customer Voltage in percentage of nominal						
Soil Resistivity (Ω-m):	100		1000		4000	
	2C	SWER	2C	SWER	2C	SWER
L50_R10	99.2	98.8	99.2	98.8	99.2	98.8
L50_R20	99.2	98.8	99.2	98.8	99.2	98.8
L100_R10	98.4	98.4	98.8	98.8	98.4	98.8
L100_R20	98.4	98.4	98.8	98.8	98.8	98.8
L200_R10	96.4	96.8	96	97.2	96.4	97.2
L200_R20	96	96.8	96	97.2	96.4	97.6
L300_R10	91.2	92.8	91.2	93.6	91.2	94
L300_R20	93.6	91.2	94	91.2	92.8	91.2

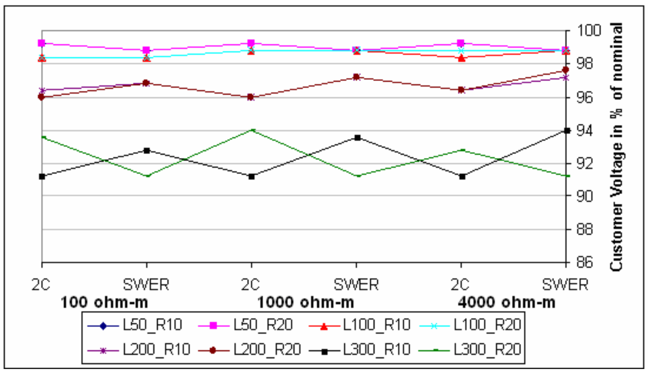


Figure 7. Calculated voltage at the customer end for the tested cases

III. COMPARATIVE TRANSIENT PERFORMANCE

The transient network response to a remote perturbation as illustrated in figure 1 was carried out. Ideally, a Dirac impulse function should be applied to obtain the impulse transient response of the network. However, from a practical standpoint, a sufficiently narrow current drawn at the service voltage level provides sufficiently accurate information about the network transient response.

The test scenario is structured as follows:

1. With all steady state loads in operation, an additional transient load current is drawn at the service voltage terminal of the distribution transformer for every one of the above described cases.
2. The peak value of the current pulse is maintained constant at 90 A peak by using a limiting impedance and by controlling the switch closing prior to voltage zero crossing. Then, switch is opened at the first current zero value at the end of the current loop.
3. The transient response is extracted from the load current at the beginning of each feeder.
4. All parametric changes as used for the steady state analysis are incorporated in this study.

The results are shown in a basic format. Figure 8 shows the three pairs of perturbation currents for soil resistivities of 100, 1000 and 4000 Ω-m for a fixed line length of 50 km. The first top pair in figure 8 shows the perturbation current pulses in relationship to the service voltage. For the first pair, the perturbation is introduced as follows:

1. For the two conductor circuit, the current pulse is drawn at the first cycle of the voltage.
2. For the SWER line, the current pulse is drawn at the third cycle of the voltage.
3. For the next pairs, the current pulses are shifted by two cycles from the previous pairs.

This sequential switching was aimed at obtaining the signal signatures on every feeder at the substation devoid of any possible mutual interference from the other feeders. The corresponding responses are depicted at the bottom graph in figure 8.

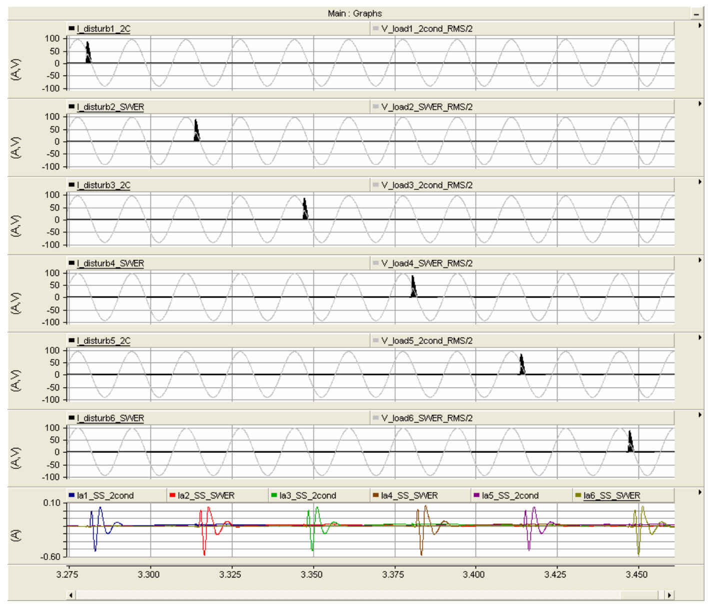
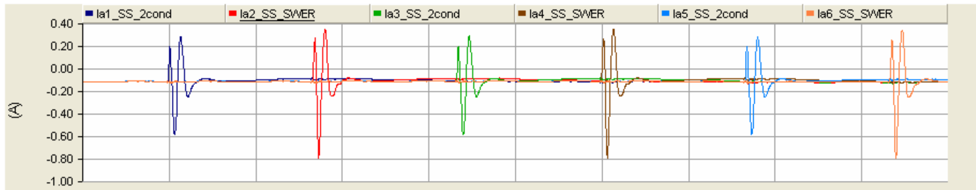


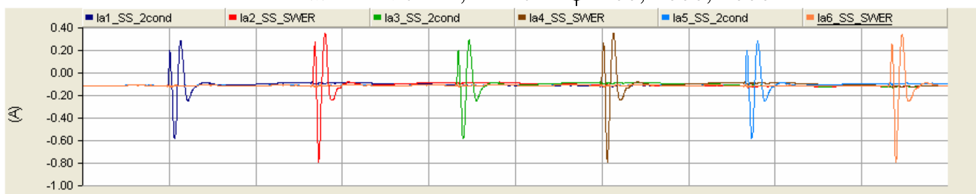
Figure 8. Transient disturbance at every tested circuit and response registered at the substation (lower trace)

Figure 9 depicts the transient response of all of the tested circuits including the parametric variations described in the steady state analysis section. The peak values for each transient response are tabulated in table 6 and plotted in figure 10.

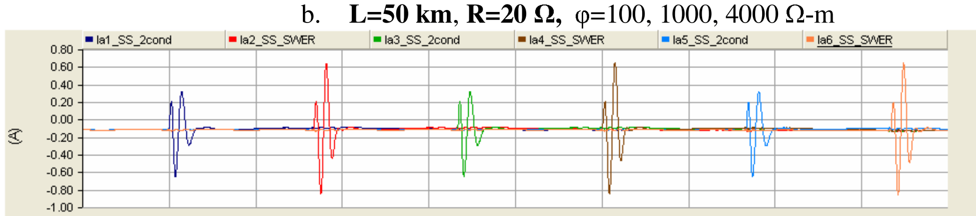
Sensitive parameters regarding transient response based on these studies turn out to be the line length and to a much lesser extent the grounding resistance of the distribution transformer at the far end. The effects of soil resistivity is found to be minimal, despite the wide range of values used in the study. The results in figure 10 place the largest transient peaks on the 100 km SWER line case, with the remaining cases showing the expected trend of decreasing peak amplitudes with increasing line length. The discrepancy on why the maximum signal values are not related to the shortest line (50 km) may have to do with natural resonant frequencies of the system at the particular 100 km SWER line length. Further analysis will be aimed at explaining this result.



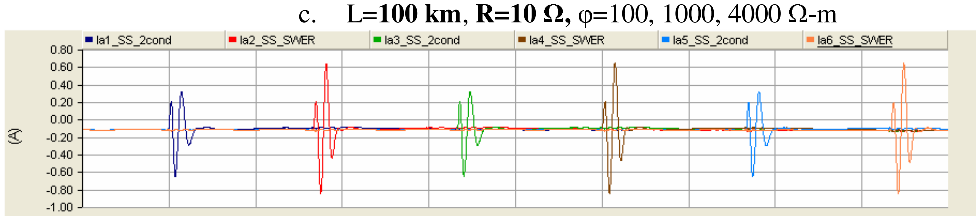
a. **L=50 km**, **R=10 Ω** φ=100, 1000, 4000 Ω-m



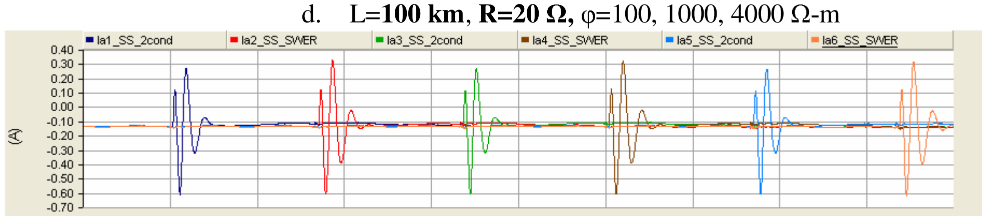
b. **L=50 km**, **R=20 Ω,** φ=100, 1000, 4000 Ω-m



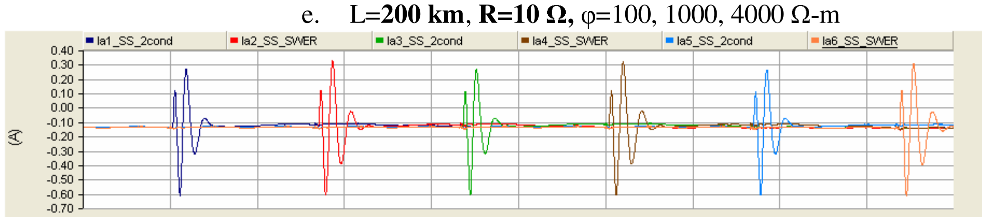
c. L=**100 km**, **R=10 Ω,** φ=100, 1000, 4000 Ω-m



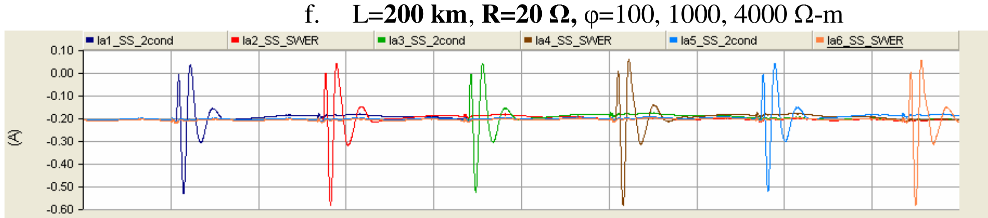
d. L=**100 km**, **R=20 Ω,** φ=100, 1000, 4000 Ω-m



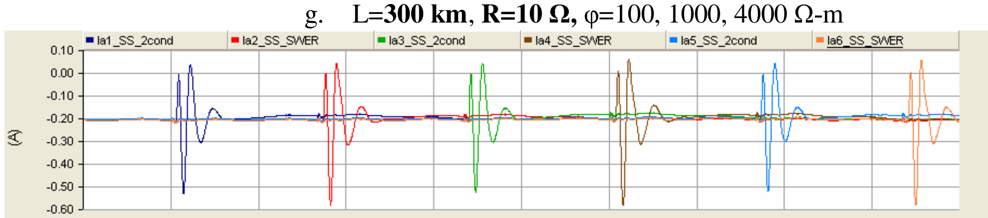
e. L=**200 km**, **R=10 Ω,** φ=100, 1000, 4000 Ω-m



f. L=**200 km**, **R=20 Ω,** φ=100, 1000, 4000 Ω-m



g. L=**300 km**, **R=10 Ω,** φ=100, 1000, 4000 Ω-m



h. L=**300 km**, **R=20 Ω,** φ=100, 1000, 4000 Ω-m

Figure 9. Transient response of all tested scenarios

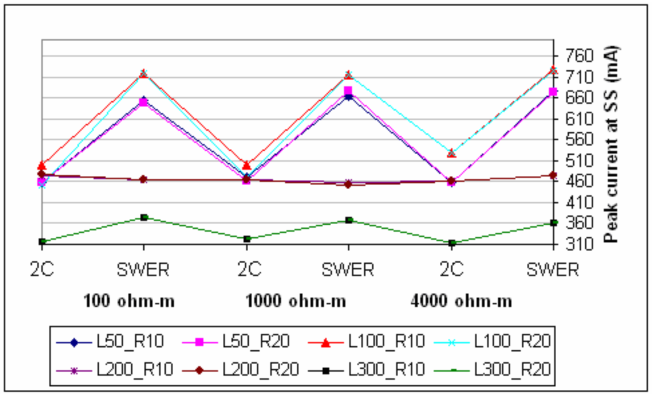


Figure 10. Comparative transient response of a SWER line relative to a 2-conductor system

IV. CONCLUSIONS

1. The total or apparent power for the assumed loading condition yields smaller values for the SWER system. This is a direct consequence of reduced losses when only one conductor is involved.
2. Increased apparent power in excess of 5% relative to the base case (L50_R10) will occur when line length is 200 km or longer, with the largest difference between the two-conductor and the SWER lines at ρ=1000 Ω-m.
3. Power factor throughout the tested scenarios is practically unchanged for the 2-conductor and the SWER line.
4. Voltage decrease to around 94% and lower relative to nominal will occur for line lengths 300 km and above. This is somewhat more pronounced for the SWER system. Utilities will have to implement appropriate voltage regulation measures to maintain the far end voltage within recommended levels.
5. Sensitive parameters regarding transient response based on these studies are the line length and to a much lesser extent the grounding resistance of the distribution transformer at the far end.
6. The effect of soil resistivity turns out to be minimal, despite the wide range of values used in the study. The results reveal the largest transient peaks on the 100 km SWER line case, with the remaining cases showing the expected trend of decreasing peak amplitudes with increasing line length.
7. From this study, the SWER system compares favorably with a two-conductor counterpart and for lengths below 300 km it can in fact represent a convenient alternative for utilities in serving low population density areas.

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